NASA CR-120796

(NASA-CR-120796) DEVELOPMENT OF DISPERSION STRENGTHENED NICKEL-CHROMIUM ALLOY (Ni-Cr-Th-02) SHEET FOR SPACE SHUTTLE VEHICLES, L.J. Klingler, et al (Fansteel, Inc.) 30 Dec. 1971 493 p CSCL 11F G3/17

N73-11512

Unclas 47947

DEVELOPMENT OF DISPERSION STRENGTHENED NICKEL—CHROMIUM ALLOY (Ni-Cr-ThO_2) SHEET FOR SPACE SHUTTLE VEHICLES

by

L.J. Klingler, W.R. Weinberger
P.G. Bailey and S. Baranow



FANSTEEL INC.
METALS DIVISION

prepared for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

NASA Lewis Research Center
Contract NAS 3—13490
C.P. Blankenship, Project Manager

NASA CR-120796

FINAL REPORT - PART I

DEVELOPMENT OF DISPERSION STRENGTHENED NICKEL-CHROMIUM ALLOY ($Ni-Cr-ThO_2$) SHEET FOR SPACE SHUTTLE VEHICLES.

by

L. J. Klingler, W. R. Weinberger,
P. G. Bailey and S. Baranow

FANSTEEL INC.
METALS DIVISION
Baltimore, Maryland

prepared for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

December 30, 1971

CONTRACT NAS 3-13490

NASA Lewis Research Center
Cleveland, Ohio

C. P. Blankenship, Project Manager
Materials and Structures Division

Details of illustrations in this document may be better studied on microfiche

PRECEDING PAGE BLANK NOT FILMED

FOREWORD

The developments described herein were conducted primarily at the Baltimore site of the Fansteel Metals Division; supporting chemical analyses were conducted principally at the Fansteel Muskogee plant.

Special electron microscopy studies were conducted at Drexel University under the direction of Professor Alan Lawley.

In addition to the listed authors three other Fansteel engineers contributed substantially in the following areas:

J. E. Kennedy - Foil Rolling, Reproducibility Studies, and Creep Testing

J. E. Scheer - Scale-up Process Studies

J. M. Stevens - TDNiCr Alloy Powder Production

Preceding page blank

TABLE OF CONTENTS

	Page
ABSTRACT	vii
SUMMARY	1
INTRODUCTION	4
INTERNATIONAL UNITS	6
DISCUSSION	7
I - SHEET PRODUCTION	
1. Program Requirements	7
2. Standard Process - 0.025-0.102 cm. (0.010-0.040 in.) Sheet	7
a. Fansteel Production Practice	7
b. Optimization of Consolidation and Breakdown Rolling Practices	12
c. Finalization of Sheet Rolling Procedure	77
3. Reproducibility Evaluation	144
a. Sheet Quality	145
b. Mechanical Properties	173
4. Production of 680.4 kg.(1500 lbs.) of TDNiCr Sheet	232
II - TDNiCr SHEET PROCESS DEVELOPMENT	
1. Program Requirements	255
2. Alternate Process Study	255
a. Rolling Studies on Recrystallized TDNiCr Sheet	256

TABLE OF CONTENTS

		Page
3.	TDNiCr Foil	262
	a. Baltimore Foil Rolling	262
	b. North Chicago Foil Rolling	277
	c. Toll Foil Rolling	279
	d. TDNiCr Foil Summary	287
	e. TDNiCr Foil Recommendations	287
4.	Rolling and Finishing Procedures	291
	a. Chemical Milling	291
	b. Creep Flattening	294
5.	Sheet Size Capability	302
	a. Billet Size	302
	b. Facilities	302
	c. Scale-Up Processing	304
6.	Specification Goals	317
	a. Chemical Composition	317
	b. Mechanical Properties	320
	c. Dimensional and Weight Tolerances	322
	d. Flatness	322
	e. Surface Finish	322
	f. Product Yield	323
	g. Specifications for Production TDNiCr Sheet	323

TABLE OF CONTENTS

	Page
III - ALLOY STUDIES	
1. Program Requirements	325
2. Alloy Composition Optimization	325
3. Ductility Improvement	328
a. Scouting Studies	328
b. Results of Ductility Scouting Studies	330
4. Oxidation Improvement	337
a. Program	337
b. Test Procedure	338
c. Oxidation of Modified TDNiCr Alloys	343
d. Oxidation of TDNiCr Base Alloys	344
e. Modified TDNiCrAl Alloys	361
f. Mechanical Properties TDNiCr Base Alloys	361
g. γ' Phase	363
h. Scale-Up Billet Processing	368
i. TDNiCr Alloy System Selection	375
SUMMARY OF RESULTS	378
APPENDICES	
Appendix A - Fansteel Product Specifications	387
Appendix B - Metallographic Techniques	395
Appendix C - Reproducibility Tests Data	401
Appendix D - TDNiCr Sheet Shipments	429
Appendix E - New Facilities	463
Appendix F - Cyclic Oxidation Data	477

DEVELOPMENT OF DISPERSION STRENGTHENED NICKEL CHROMIUM ALLOY ($Ni-Cr-ThO_2$) SHEET FOR SPACE SHUTTLE VEHICLES

by

L. J. Klingler, W. R. Weinberger,
P. G. Bailey and S. Baranow

ABSTRACT

A dispersion strengthened alloy, TD Nickel Chromium (TDNiCr) is being developed for use on the thermal protection system of the space shuttle at temperatures up to 1204°C(2200°F). Manufacturing processes have been developed for the fabrication of sheet and foil to specifications. Sheet has been provided to NASA Centers for other shuttle technology studies. The addition of aluminum to the basic TDNiCr composition provides outstanding oxidation resistance up to 1260°C(2300°F); aluminum levels of 2-4% are considered optimum for space shuttle application. Development of TDNiCr and TDNiCrAl alloys is being continued on Part II of the program.

SUMMARY

The dispersion strengthened alloy, TD Nickel Chromium (TDNiCr) is considered a promising candidate material which can be used without coatings for the hotter portions of the space shuttle thermal protection system. The use temperature range for TDNiCr is estimated to be 982-1204° C(1800-2200° F). The alloy has a nominal composition of Ni-20%Cr-2%ThO_2. A unique combination of elevated temperature strength, oxidation resistance, structural stability and resistance to thermal peaks make TDNiCr an excellent candidate for thermal protection systems.

A manufacturing development program was initiated as a part of the NASA Space Shuttle Technology Program to further develop TDNiCr sheet to meet the anticipated requirements for shuttle use.

The objectives of the development program were threefold:

- To develop TDNiCr sheet which would meet the technical requirements of thermal protection systems for space shuttle vehicles
- To develop a standard production process for the manufacture of sheet of the desired sizes and gauges
- To provide sheet for NASA technology programs.

The goals of the Part I program have been met and exceeded. Processes have been developed and TDNiCr sheet and foil have been manufactured and delivered to NASA Centers for further studies. A new alloy material has been developed which offers outstanding oxidation resistance. A listing of these accomplishments follows:

- A standard process has been established for the production of TDNiCr sheet which meets the goals of this program and the Fansteel specifications for the gauge range 0.025-0.102 cm.(0.010-0.040 in.) in sheet sizes of 46 x 91 cm. (18 x 36 in.).
- A total of 821.1 kg.(1808.6 lb.) of TDNiCr sheet was manufactured and shipped to the NASA Centers or their Contractors for space shuttle technology studies.
- High quality TDNiCr foil in gauges from 0.005-0.013 cm.(0.002-0.005 in.) has been fabricated by cold tension rolling on a Sendzimir mill at widths exceeding the goal value of 30 cm.(12 in.).
- Process studies have shown that an increase in input billet size from 45.4 kg.(100 lb.) to 68.0 kg.(150 lb.) is necessary to produce the goal sizes of sheet 61 x 152 cm. (24 x 60 in.).

Process improvement studies have been made to upgrade the tolerances, flatness and surface finish of the TDNiCr sheet.

Two special purpose furnaces were designed and built for use in the process studies and permit the production of 61 x 152 cm.(24 x 60 in.) sheet.

• Minor alloy studies were made to try to improve the ductility behavior of TDNiCr ---- hydride and halide additions offer some promise for improvement.

• Alloy studies were made to improve the behavior of TDNiCr at 982-1204°C(1800-2200°F) under the severe oxidational environment to be experienced by the space shuttle. The addition of Al in the Ni-Cr alloy matrix provided cyclic oxidation protection under the most severe test conditions at temperatures up to 1260°C(2300°F).

A Part II continuation of the program that includes development of an advanced alloy is now in process. The basic alloy system which has been chosen for further study is Ni-Cr-Al-ThO_2 alloys plus the possible addition of yttrium; the chromium levels will be 12-22%, the aluminum levels 2 to 4%.

INTRODUCTION

The dispersion strengthened alloy, TD Nickel Chromium (TDNiCr) is considered a promising candidate material which can be used without coatings for the thermal protection system of space shuttle vehicles exposed in the 982-1204°C(1800-2200°F) temperature range. The alloy has a nominal composition of Ni-20%Cr-2%ThO_2. A unique combination of elevated temperature strength, oxidation resistance, structural stability and resistance to thermal peaks make TDNiCr a potential choice for thermal protection systems.

Fansteel development data have indicated that improvements in oxidation behavior and in ductility might extend the potential utility of TDNiCr. It was also recognized that the small scale process previously utilized to manufacture sheet in the desired product gauge range of 0.025-0.102 cm. (0.010-0.040 in.) must be improved to yield reproducible sheet with improved shape, finish, and tolerances.

A manufacturing development program was initiated as a part of the NASA Space Shuttle Technology Program to further the development of TDNiCr sheet.

The objectives of the program were threefold:

- To develop TDNiCr sheet which would meet the technical requirements of thermal protection systems for space shuttle vehicles.
- To develop improved production processes for the manufacture of sheet of the desired sizes and gauges.

- To provide sheet for NASA technology programs.

The work was divided into three sub-programs which were conducted concurrently:

I - Sheet Production

II - Sheet Process Development

III - Alloy Studies

This program was accomplished under NASA Contract NAS 3-13490 covering the period from April 23, 1970 to June 22, 1971. The original contract has now been extended an additional sixteen months to October 22, 1972. The work performed on the original contract is covered by this report and is referred to as Part I. The work subsequent to June 23, 1971 will be referred to as Part II, and will be reported at a later date.

INTERNATIONAL UNITS

The International System of Units, SI Units is used as the primary system of units in this report. The customary units are given as secondary units, parenthetically following the primary units. In the case of large "Tables", two versions are given, one in SI Units, and one in Customary Units.

The SI Units used in this report together with their symbols are listed below:

Physical Quantity	Name of Unit	Symbol
Length	meter	m
Length	centimeter	cm
Length	micron	μ
Mass	kilogram	kg
Time	second	s
Time	hour	hr
Temperature	degree centigrade	°C
Force	newton	N
Force	meganewton	MN
Stress	meganewtons per square meter	MN/m^2

DISCUSSION

I - SHEET PRODUCTION

1. Program Requirements

In order to provide TDNiCr sheet for evaluation and use by NASA Centers, the following requirements were established:

- A standard process shall be developed for the production of TDNiCr sheet, 46 x 91 cm.(18 x 36 in.), in the gauge range of 0.051-0.102 cm.(0.020-0.040 in.) that conforms to the Fansteel Product Specifications S-TC-S-01-R-1, December 1, 1969 and S-DMM-S-01-R-0, January 1, 1969. Copies of the specifications are included as Appendix A to this report. The Metallographic Techniques utilized in this program are described in Appendix B.
- An interim process shall be developed for the production of sheet, 46 x 91 cm.(18 x 36 in.), in the gauge range of 0.025-0.048 cm.(0.010-0.019 in.).
- At least 680.4 kg.(1500 lbs.) of TDNiCr sheet shall be produced via the standard and interim processes for delivery to NASA Centers.

2. Standard Process - 0.025-0.102 cm.(0.010-0.040 in.) Sheet

a. Fansteel Production Practice

The process sequence shown in Figure 1 had been established and was being used by Fansteel Metals Division at the start of this NASA contract in April, 1970. The process was developed to produce TDNiCr sheet in gauges from 0.025 cm.

1. Powder Manufacture
   - Ni-20Cr-2ThO_2 - Nominal Composition

2. Hydrostatic Compaction
   - Mylar liner in rubber boot - 414 MN/m^2 (60,000 psi)
   - 90.7 kg.(200 lb.) unit - 20.32 Ø x 50.8 cm. long (8 Ø x 20 in. long) - Nominal compact size
   - 45.36 kg.(100 lb.) unit - 8.27 x 21.60 x 45.72 cm. (3-1/4 x 8-1/2 x 18 in.) - Nominal compact size

3. Sinter
   - 954° C(1750° F) in dry H_2 - Compact in mild steel can
   - Dew Point controlled to -56.70° C(-70° F)

4. Consolidate
   a.) Extrusion
      - Preheat canned unit to 954° C(1750° F)
      - Extrude 20.3 Ø to 2.54 x 15.24 cm.(8 Ø to 1 x 6 in.) Nominal sheet bar size

   b.) Forging
      - Preheat canned unit to 1010° C(1850° F) in H_2 atmos.
      - Forge in closed die to 4.45 x 25.4 x 50.8 cm. (1-3/4 x 10 x 20 in.) - Nominal size

5. Condition
   - Sandblast & pickle decan. Cut & flatten extruded sections.
   - Machine and grind
     a.) Extruded sheet bars - 20.32 x 13.97 x length cm. (0.8 x 5-1/2 x length in.)
     b.) Forged sheet bar - 4.13 x 22.86 x 45.72 cm. (1-5/8 x 9 x 18 in.)
   - Sample for chemistry and ThO_2 size and distribution.

6. Can for Breakdown Rolling
   - Preheat canned forged unit to 1010° C(1850° F)
   - Breakdown roll from 4.13 to 2.54 cm.(1-5/8 to 1.0 in.)
   - Cool
   - Preheat canned extrusion and forged units to warm rolling temperature - 649-816° C(1200-1500° F) range
   - Isothermally roll to intermediate gauge, 0.254 cm.(0.1 in.)

7. Condition
   - Decan, grind condition, chemical clean

8. Rolling to Gauge
   - Recan in mild steel cover plates
   - Preheat units to warm rolling temperature - 649-816° C (1200-1500° F) range
   - Isothermally roll to gauge (reheat as required)

9. Condition
   - Chemical clean
   - Grind and belt sand condition

10. Heat Treatment
    - Recrystallization heat treatment - 1177° C(2150° F)/2 hrs.
    - Dry hydrogen

11. Finishing
    - Flatten if required
    - Wide belt sand
    - Hand polish

12. Shear to Size
    - In-process inspection for gauge and finish
    - Shear to finish size
    - Sample

13. Inspection
    - Inspect size, gauge, finish, flatness
    - Test to specifications

14. Ship

FIGURE 1

FANSTEEL PROCESS SEQUENCE FOR TDNiCr SHEET

(0.010 in.) to 0.191 cm.(0.075 in.) inclusive to Fansteel Specification S-TC-S-01-R-1 and S-DMM-S-01-R-0.

The powder is manufactured at the Baltimore Plant. The production capacity has been increased by the installation of additional units. The plant now has a rated capacity of 45,360 kg.(100,000 lbs.) of powder per year. A small scale pilot plant is used for alloy studies which only require 4.54 kg.(10 lbs.) of powder per unit. The powders are exposed to air at the end of the manufacturing cycle and hence must be treated in a reducing atmosphere to remove adsorbed moisture and surface oxidation prior to consolidation to a dense slab.

Hydrostatic compaction is used to increase the density from the nominal 30-40% flow density of the powder to 60-70% in the hydrostatically compressed powder. Various types of hardware have been utilized to produce compacts of the desired sizes. A Mylar plastic sleeve prevents adhesion and cutting the wall of the rubber boot. The Mylar, however, wrinkles as the compact size is reduced resulting in a wrinkled surface on the compact.

The sinter treatment provides for the elimination of adsorbed water vapor and surface oxidation prior to consolidation. It also removes any leakage resulting from the previous hydrostatic compaction step. The temperature is controlled both to inhibit ThO_2 growth and to prevent shrinkage which could seal up the pore structure and not permit the evolution of water vapor from the interior of the compacts.

The consolidation of the sintered compact to dense slab for rolling was done by extrusion of an 20.32 cm.(8 in.) diameter round billet to rectangular sheet bar, 2.54 x 15.24 cm. (1 x 6 in.) nominal cross section, or forging a rectangular billet in a closed die. Both techniques produce dense slab which can be rolled to sheet. The choice of method has been keyed to the product size desired. More flexibility is available by extrusion but it is limited in terms of inability to be scaled up to large size units for the rolling mill. Roll consolidation of TDNi had been practiced previous to the initiation of this contract but had not been practiced with TDNiCr.

Breakdown rolling at 1010°C(1850°F) is practiced only on the forged sheet bar. The length is rolled to 55.88 cm.(22 in.) nominal and the thickness is then reduced to 2.54 cm.(1.0 in.) by cross rolling. The 55.88 cm. (22 in.) dimension becomes the width dimension for subsequent isothermal rolling. The 2.54 x 15.24 cm.(1 x 6 in.) extruded sheet bars are not rolled at 1010°C(1850°F) but are cut into the desired lengths for the isothermal rolling. Heavier extruded sheet bars up to 5.08 x 15.24 cm.(2 x 6 in.) have been manufactured; these require rolling at 1010°C(1850°F) to 2.54 cm.(1.0 in.) thickness.

The 2.54 cm (1.0 in.) thick slabs are warm rolled at temperatures in the 649°C-843°C(1200°F-1500°F) range to an intermediate gauge plate size of 0.25 to 0.51 cm.(0.1 to 0.2 in.). The choice of temperature has been a function of

the product size desired, the gauge and the furnacing available for heating.

After conditioning, isothermal rolling to gauge has been practiced in mild steel cover plates. At gauges <0.102 cm. (<0.040 in.) pack rolling is utilized in which two or more sheets of TDNiCr are inserted between the cover plates. Re-canning is done as required, to maintain the product sheet shape, and as the length increases exceed the capacity of the furnacing.

The recrystallization anneal is conducted in a Sunbeam gas fired furnace. A programmed heat-up in argon and then dry H_2 is used to provide uniform heating.

Wide belt sanding has been used almost exclusively for finishing sheet in gauges down to 0.038 cm.(0.015 in.). It was recognized that other finishing techniques would be required to produce the desired finish requirements in thin sheets of gauges <0.038 cm.(<0.015 in.).

Cumulative yield data from input powder for both the extrusion and forge consolidation routes were as follows:

Conditioned 2.54 cm.(1.0 in.) slab - 70%

Intermediate Gauge Plate - 55%

Product Sheet

0.152 cm.(0.060 in.) gauge - 30%

0.025 cm.(0.010 in.) gauge - 20%

b. Optimization of Consolidation and Breakdown Rolling Practices

The initial work as shown on the Flow Chart, Figure 2, reproduced from Exhibit A of the contract, was to fix the processing practice for manufacturing 45.36 kg.(100 lb.) sheet bar units. The work plan called for the utilization of 10 - 45.36 kg.(100 lb.) units for this part of the program.

A change was made in the consolidation practice shortly after the initiation of the contract. The group of ten units planned for the forging studies was reduced to a group of four units as shown in the Modified Flow Chart, Figure 3.

The remaining six billets were consolidated by an alternate technique, roll consolidation. This technique was being developed by Fansteel Inc. for TD Nickel. It combines the consolidation and breakdown rolling operations; thus offering potential improvements in the areas of yield, scheduling and cost. Two TDNiCr units were used to determine the feasibility of the process and then the remaining group of four units was utilized for development of the process. The identical sintering and forging temperature variables used for the forged billets were employed for the roll-consolidation billets. By this means, an evaluation of material fabricated by the forged route technique and the roll-consolidation technique was accomplished.

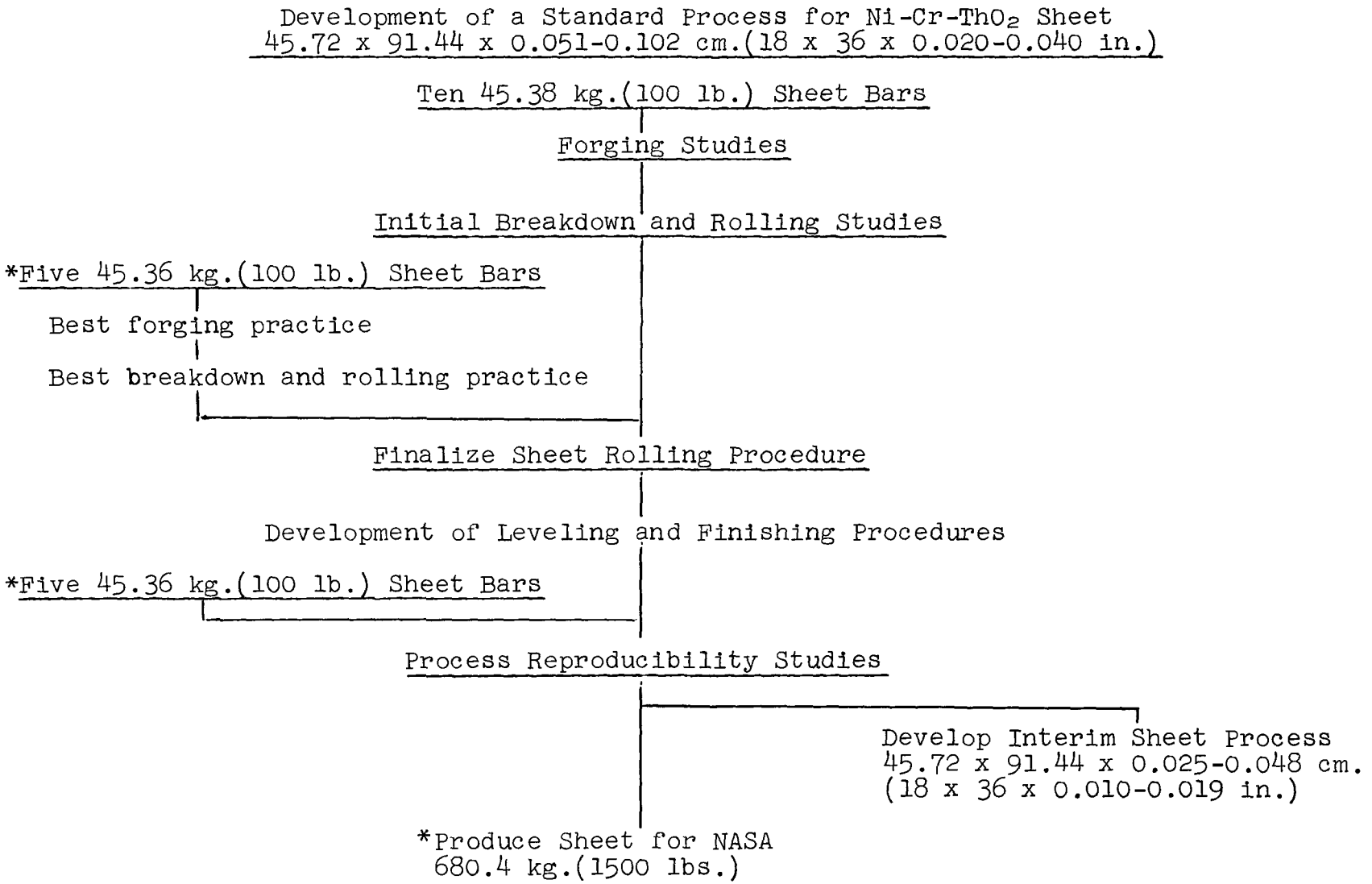


FIGURE 2

FLOW CHART

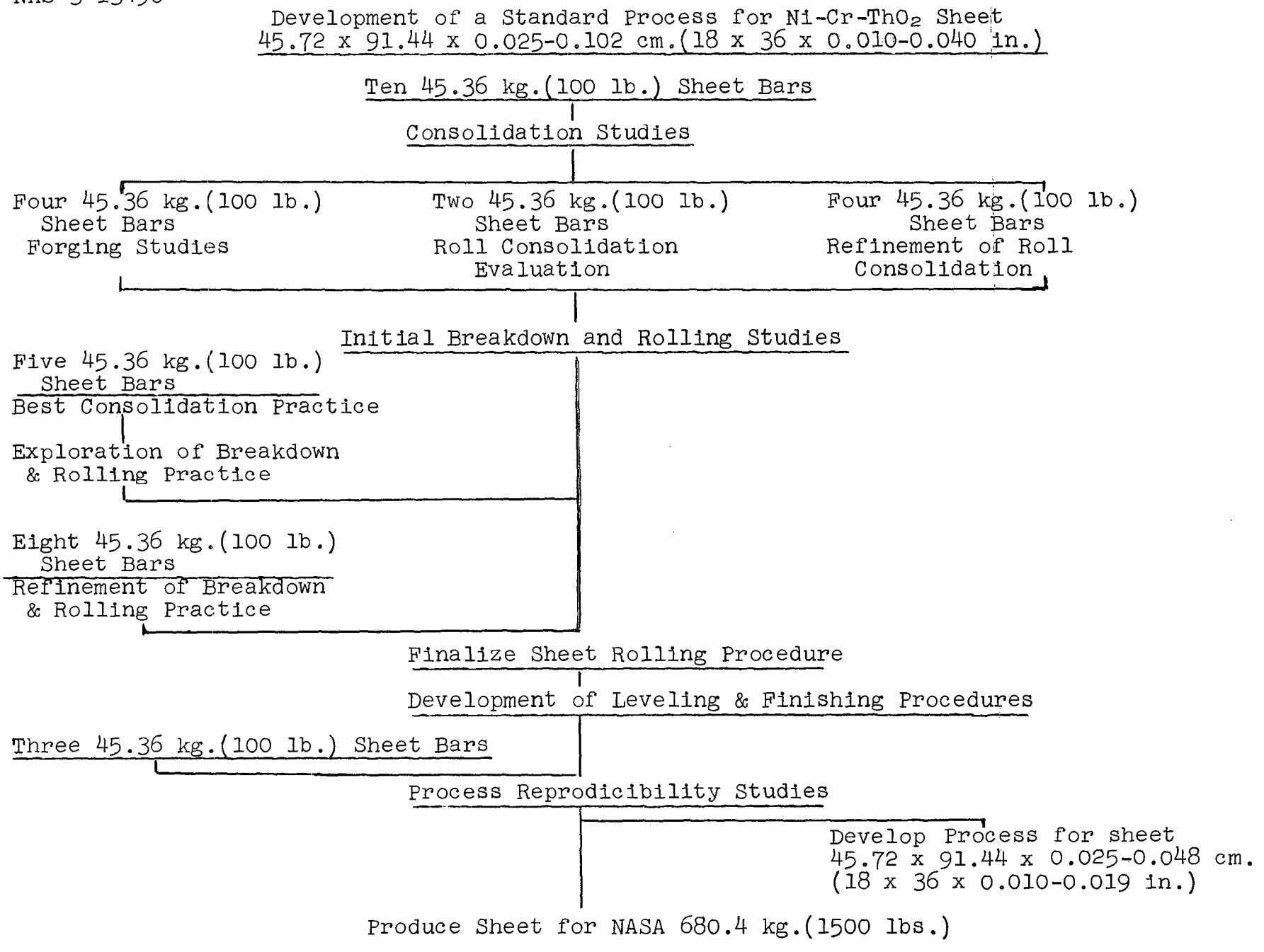


FIGURE 3 - MODIFIED FLOW CHART

The powder was processed into 45.36 kg.(100 lb.) units having the following heat numbers:

Forge Consolidated	Roll Consolidated
3278	3304
3279	3305
3281	3280
3283	3282
	3284
	3285

A change in the hydrostatic compaction process was made early in the program. Billets 3304 and 3305 were made by the previous standard technique using a Mylar plastic liner. The irregular surface due to wrinkling of the Mylar can be seen in Figure 4.

The improved compaction process utilizes a rectangular rubber boot supported externally by a close fitting perforated metal form. The boot is filled directly with powder. Special sealing techniques are used to keep the compaction fluid from entering the powder compact. This technique produces a smooth surface as shown in Figure 5.

The compacted billets were canned in mild steel for the sintering operation as shown in Figure 6.

Subsequently, the sintered billets were subjected to a hot densification process carried out by either forge consolidation or roll consolidation.

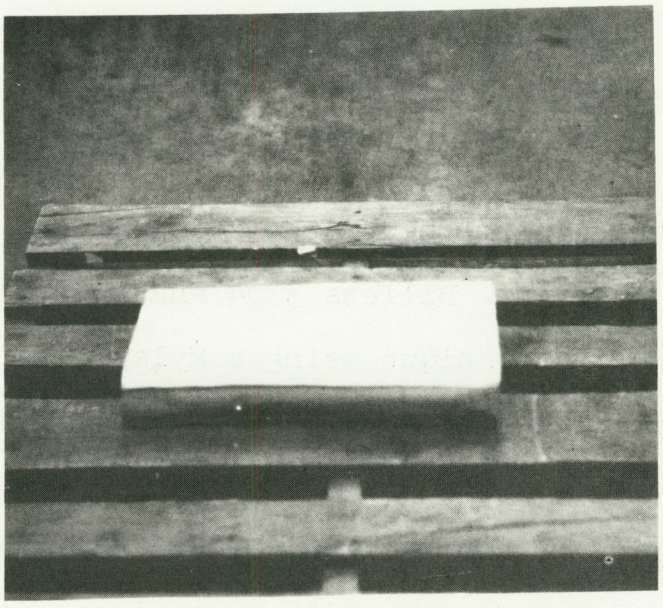


FIGURE 4

TYPICAL 45.36 kg.(100 lb.) TDNiCr HYDROSTATIC COMPACT
(MYLAR PLASTIC LINER)

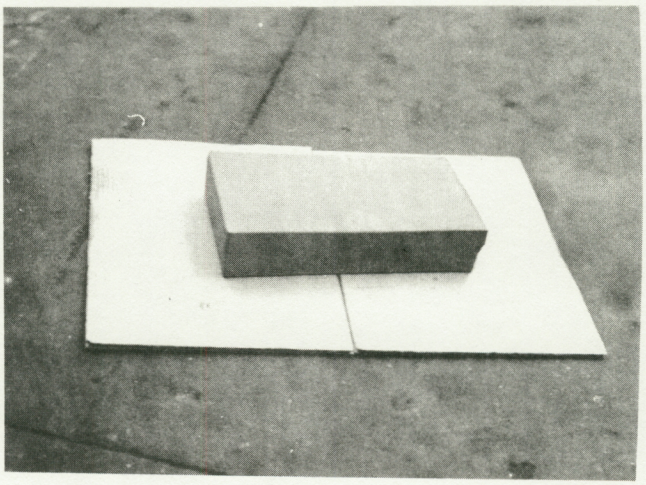


FIGURE 5

IMPROVED 45.36 kg.(100 lb.) TDNiCr HYDROSTATIC COMPACT

(RUBBER BOOT - NO LINER)

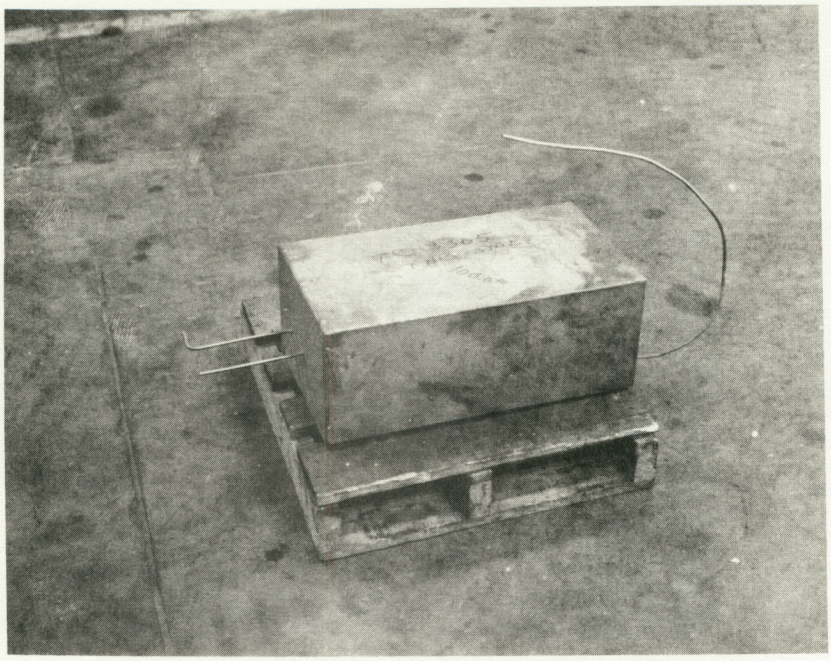


FIGURE 6

TDNiCr COMPACT

CANNED FOR SINTERING OPERATION

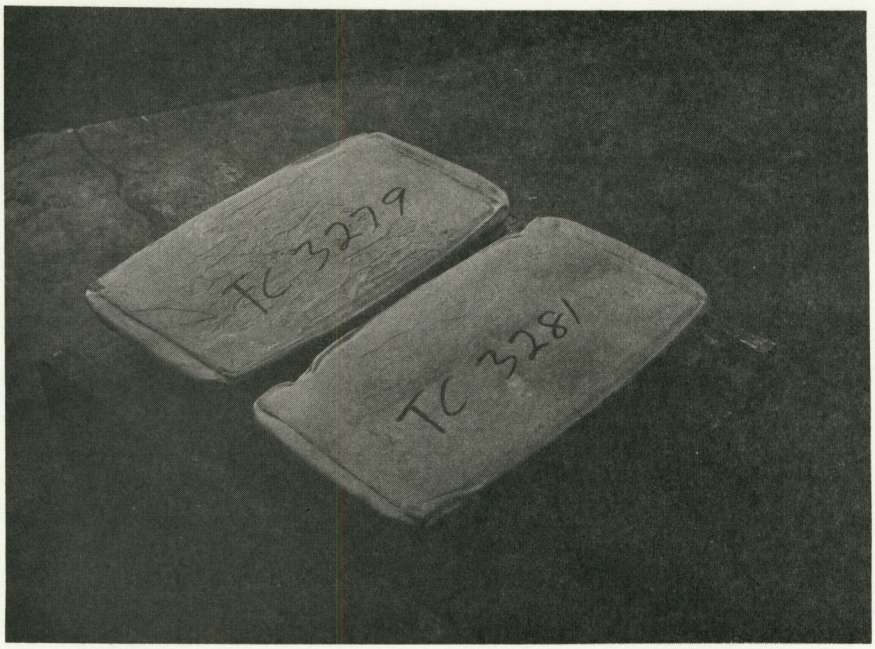
(1.) Forge Consolidation

The four units for the forge consolidation study were Heats 3278, 3279, 3281 and 3283. Sintering and consolidation temperatures were varied for these billets. Two billets were sintered at 954° C(1750° F) and two at 1066° C(1950° F). Two billets were forge consolidated at 1010° C(1850° F) and two at 1066° C(1950° F).

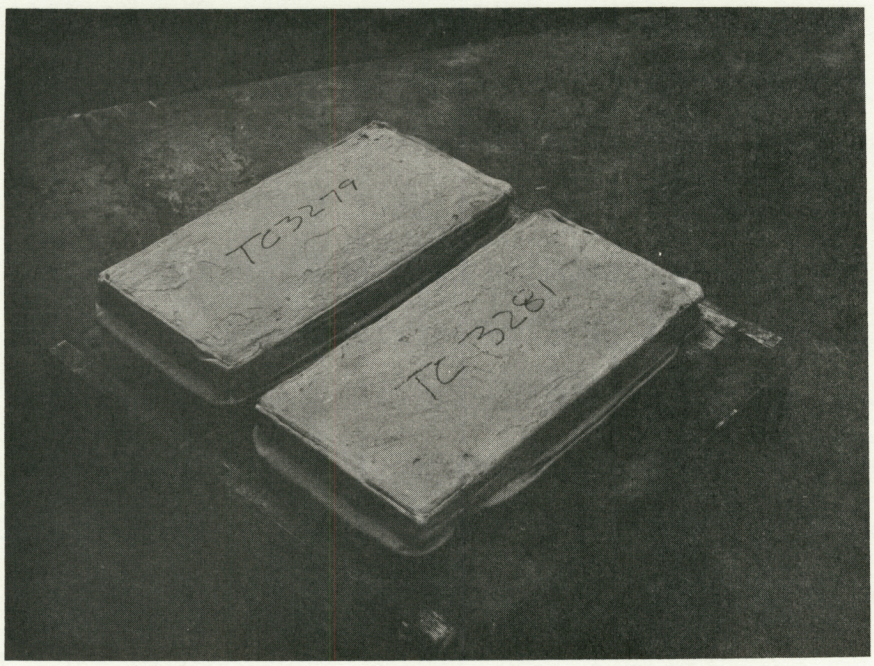
Typical 45.36 kg.(100 lb.) forged units are shown in Figure 7. A typical unit after forging and pickle decanning is shown in Figure 8. Further processing of the four forged units consisted of conditioning by machining and grinding of the pickle decanned slabs. The resultant product of this operation may be noted in Figure 9.

The units were recanned in mild steel as shown in Figure 10 and rolled at either 1010° C(1850° F) or 1066° C (1950° F) to an approximate thickness of 2.54 cm.(1.0 in.). At this point, the unit was air cooled to a lower temperature for warm rolling to 0.25 to 0.64 cm.(0.100 to 0.250 in.) in thickness, appearing similar to the plate shown in Figure 11. The steel cans were then mechanically stripped resulting in intermediate gauge plate as shown in Figure 12.

Further processing consisted of edge and end trimming to remove all cracking, chemical cleaning and shearing each intermediate plate into four equal length segments. One segment of each of the four forgings at intermediate gauge was then recanned in 0.152 cm.(0.060 in.) thick mild steel and rolled, Figure 13, at 760° C(1400° F), furnace temperature, to



TOP



BOTTOM

FIGURE 7

TYPICAL AS-FORGED TDNiCr BILLETS



FIGURE 8

FORGED TDNiCr BILLET

PICKLE DECANNED



FIGURE 9

DECANNED FORGED TDNiCr BILLET

CONDITIONED BY MACHINING & GRINDING

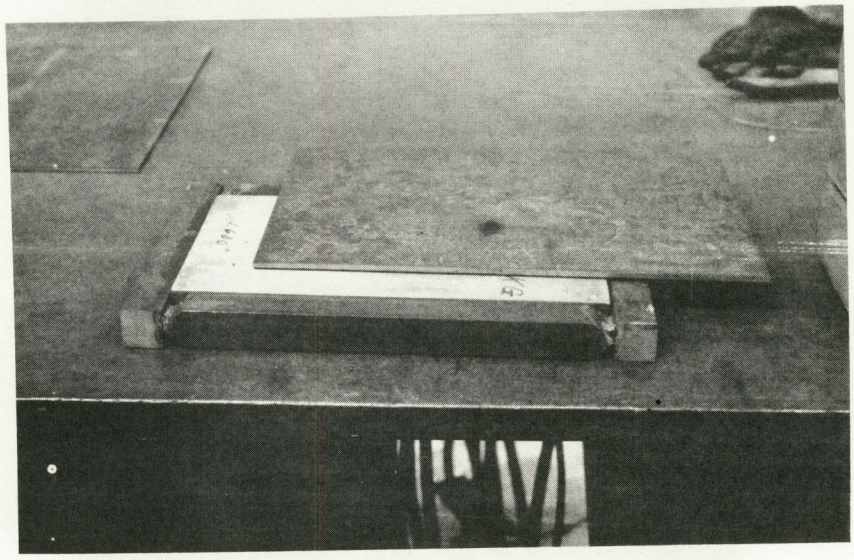


FIGURE 10

CONDITIONED FORGED TDNiCr BILLET

CANNING COMPONETS FOR ROLLING

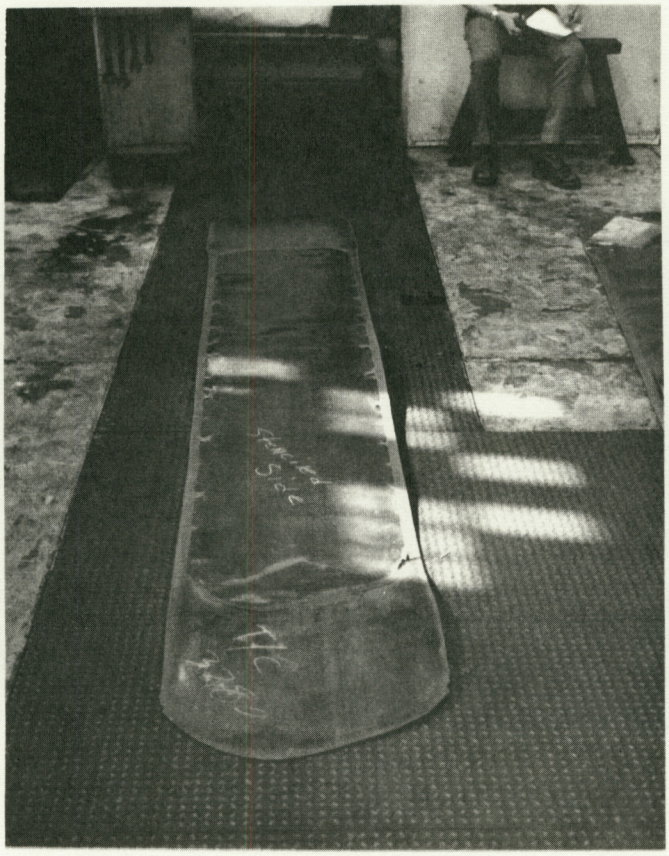


FIGURE 11

INTERMEDIATE GAUGE TDNiCr PLATE

CONTAINED IN MILD STEEL CAN



FIGURE 12

DECANNED INTERMEDIATE GAUGE TDNiCr PLATE

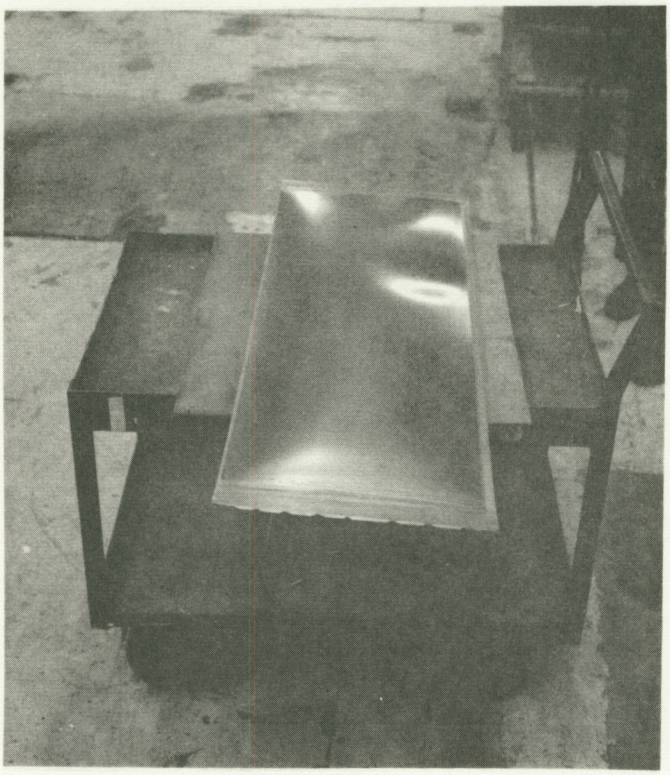


FIGURE 13

INTERMEDIATE GAUGE PLATE

IN PROCESS OF ROLLING TO GAUGE

gauges of 0.102 cm.(0.040 in.) and 0.051 cm.(0.020 in.) inches.

At these gauges, the sheet was subjected to a recrystallization heat treatment of 1177°C(2150°F) for two hours. After heat treatment specimens at 0.102 cm.(0.040 in.) and 0.051 cm.(0.020 in.) were obtained for testing and metallurgical evaluation.

Evaluation criteria employed during this investigation included the following:

Forged sheet bar yield

Edge cracking

Sheet properties vs. gauge

Breakdown plate yields

Sheet yields

Cr_2O_3 and ThO_2 parameters in plate and sheet

The data are summarized in Table 1 for the four - 45.36 kg.(100 lb.) units fabricated for the initial work carried out in the program.

Two sintering temperatures, 954°C(1750°F) and 1066°C(1950°F) were studied; the lower temperature was employed prior to initiation of this work. However, 954°C(1750°F) was considered lower than that necessary to reduce available chromium oxide present. For this reason, a temperature of 1066°C(1950°F) was selected which would not cause an increase in the thoria particle size to a size detrimental to mechanical properties.

TABLE 1

FORGED ROUTE PROCESSING PARAMETERS AND YIELDS

Operation	Heat No. 3279	3281	3283	3278
Starting Powder Weight kg	45.36	45.36	45.36	40.84
Sinter Temp.	954°C	1066°C	954°C	1066°C
Consolidation Method	Forge	Forge	Forge	Forge
Consolidation Temp.	1010°C	1010°C	1066°C	1066°C
Conditioned Sheet Bar Size	4.06x23.26x 41.59 cm.	4.14x 22.07x 43.50 cm.	4.14x 22.86x 42.86 cm.	3.63x 23.18x 41.28 cm.
Conditioned Weight kg	32.70	32.89	34.34	29.44
Forged Sheet Bar Yield	72.1%	72.5%	75.7%	72.0%
Post Forge H.T.	None	1010°C	None	1066°C
Breakdown Rolling Temp.	1010°C	1010°C	1066°C	1066°C
Breakdown Rolled Thickness	2.97 cm.	2.97 cm.	2.97 cm.	2.49 cm.
Decan Gauge	0.35 cm.	0.29 cm.	0.28 cm.	0.30 cm.
Yield after Trim at Decan Gauge	56.5%	58.4%	60.8%	57.4%

TABLE 1

FORGED ROUTE PROCESSING PARAMETERS AND YIELDS

Operation	Heat No. 3279	3281	3283	3278
Starting Powder Weight lb.	100.0	100.0	100.0	90.0
Sinter Temp.	1750°F	1950°F	1750°F	1950°F
Consolidation Method	Forge	Forge	Forge	Forge
Consolidation Temp.	1850°F	1850°F	1950°F	1950°F
Conditioned Sheet Bar Size	1.6"x9-5/32" x16-3/8"	1.63"x 8-11/16"x 17-1/8"	1.63"x9" x16-7/8"	1.43"x9-1/8" x16-1/4"
Conditioned Weight lb.	72.1	72.5	75.7	64.9
Forged Sheet Bar Yield	72.1%	72.5%	75.7%	72.0%
Post Forge H.T.	None	1850°F	None	1950°F
Breakdown Rolling Temp.	1850°F	1850°F	1950°F	1950°F
Breakdown Rolled Thickness	1.17"	1.17"	1.17"	0.98"
Decan Gauge	0.135"	0.115"	0.114"	0.117"
Yield after Trim at Decan Gauge	56.5%	58.4%	60.8%	57.4%

A forging temperature (consolidation) and breakdown rolling temperature of 1010° C(1850° F) was employed prior to initiation of this work. An alternate temperature of 1066° C(1950° F) was selected for evaluation during this program in an effort to determine effect upon fabricability during forging and roll breakdown as reflected in forged slab, plate and sheet yields. Also, possible effects upon chromium oxide content and thoria size as a result of increased forging temperature and breakdown rolling temperature were evaluated. Post forge heat treatments were included on two of the billets using the same temperature as for the subsequent hot rolling.

The data in Table 1 indicate that no large change of yield at either conditioned sheet bar stage or at decanning gauge plate may be attributed to sintering temperature and/or consolidation temperature. The 2 to 3 percent differences that do occur appear to be typical process variances and would therefore be considered insignificant.

It may also be pointed out that no significant differences in the extent of edge cracking as indicated by yield on decanned plate at an intermediate gauge of approximately 0.254 cm.(0.100 in.) was noted as a result of a change in the breakdown rolling temperature.

The yield values for conditioned sheet bar and intermediate gauge plate are consistent with those given previously for Fansteel commercial practice.

(2.) Roll Consolidation

Two billets, Heats 3304 and 3305, were processed by roll consolidation initially to determine the feasibility of this technique for the TDNiCr alloy. The billets were compacted and sintered at 954°C(1750°F). After sintering the compacts were canned in a picture frame configuration of mild steel with a cavity volume approximately equal to the volume of the compact at full density. Hand fitted cover plates were welded to the faces of the picture frame to enclose the sintered compacts. Typical can configuration and actual canned 45.36 kg.(100 lb.) units are shown in Figures 14 and 15 respectively. Next, the canned units were preheated at 1010°C(1850°F) maintaining a hydrogen atmosphere within the cans during heat up. The units were roll consolidated in one pass on the rolling mill. Rolling was continued at 1010°C (1850°F) to a thickness of approximately 3.81 cm.(1-1/2 in.). The units were then cooled to room temperature and visually examined. Further rolling appeared feasible in the consolidation picture frame cans. One unit was subsequently rolled to approximately 0.64 cm. (1/4 in.) thick and one unit to 0.48 cm.(3/16 in.) thick using the standard warm rolling technique for TD Nickel Chromium. After decanning, surface irregularities were noted. They were believed to be caused by intrusion and bonding of the cover plate material, and edge cracking due to side restraints ---- both caused a lower yield than anticipated.

One segment of Heat 3304 approximately 0.330 x 50.80 x 76.20 cm.(0.130 x 20 x 30 in.) and one segment of

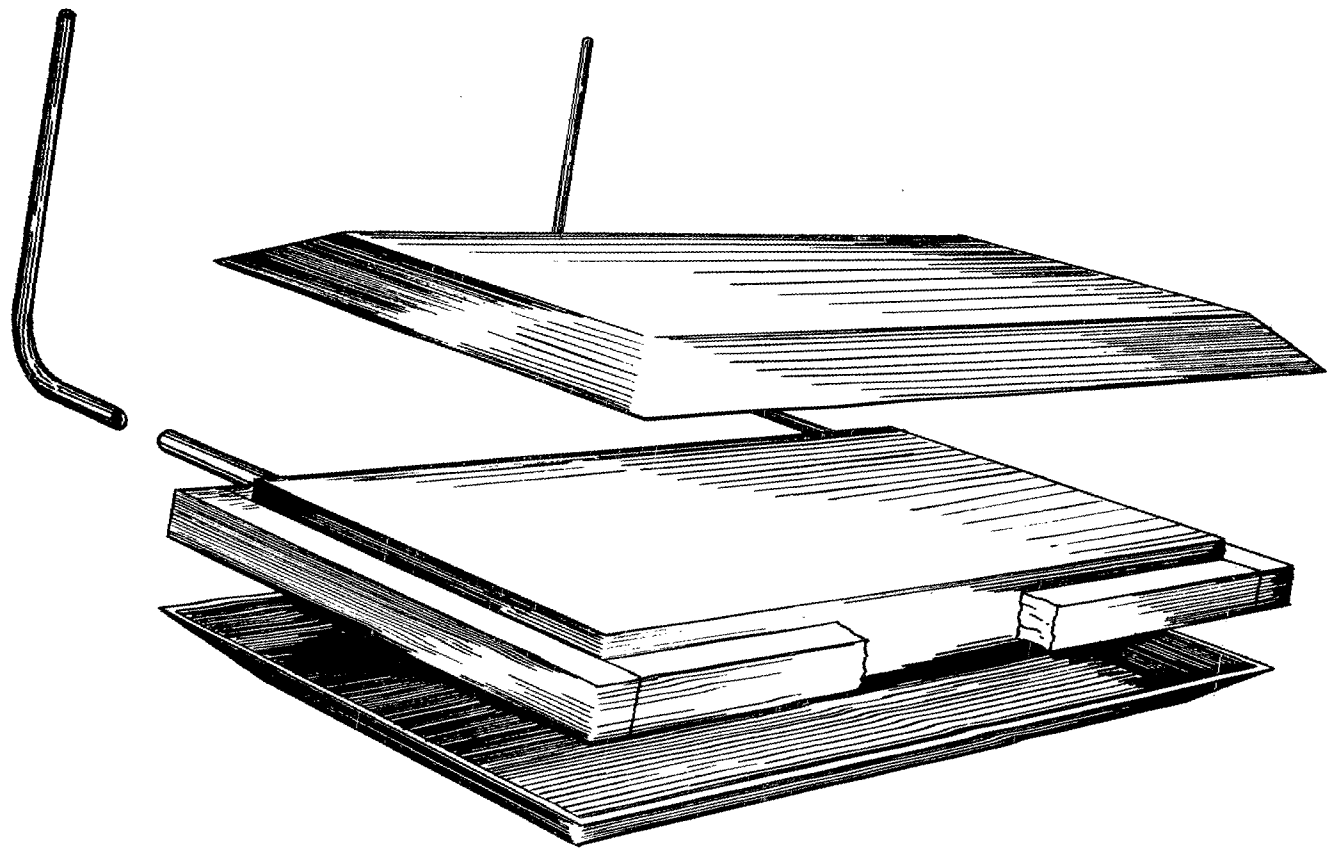


FIGURE 14
ROLL CONSOLIDATION CAN CONFIGURATION

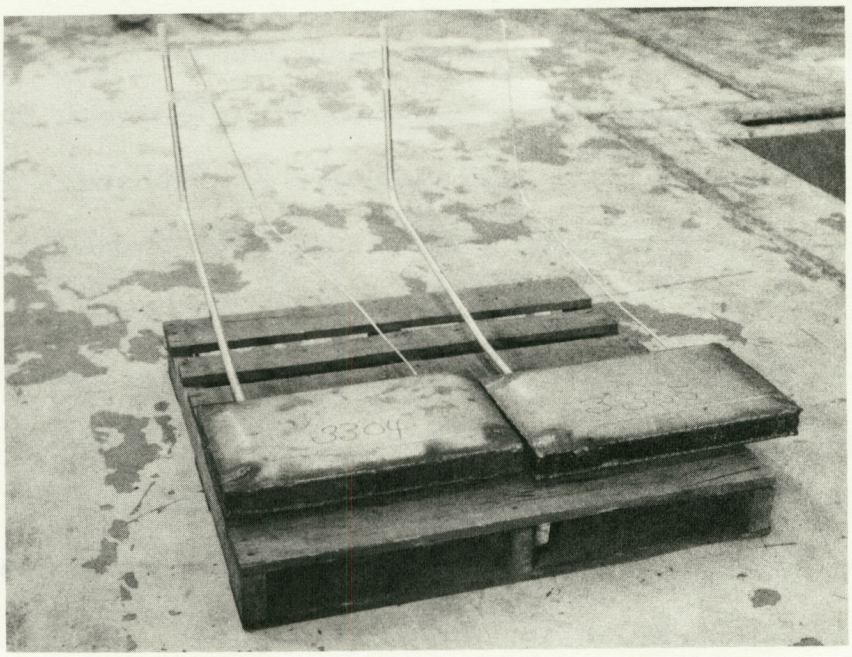


FIGURE 15

TDNiCr COMPACTS

CANNED FOR ROLL CONSOLIDATION

Heat 3305 approximately 0.508 x 50.80 x 76.20 cm.(0.200 x 20 x 30 in.) were conditioned by wide belt sanding and local hand grinding in an effort to condition out surface irregularities. Each piece was subsequently recanned in 0.152 cm.(0.060 in.) thick mild steel cover plates and processed into sheet at gauges of 0.102, 0.076, 0.051 and 0.036 cm.(0.040, 0.030, 0.020 and 0.014 in.). Samples of each gauge were subjected to a recrystallization heat treat at 1177°C(2150°F) for two hours in dry hydrogen atmosphere. Mechanical testing was then carried out yielding the results shown in Table 2.*

As indicated in Table 2, all the material fabricated by the roll-consolidation technique and further processed to sheet at gauges of 0.036, 0.051, 0.076 and 0.102 cm.(0.014, 0.020, 0.030 and 0.040 in.) satisfied the requirements of Fansteel Product Specification S-TC-S-01-R-1 dated December 1, 1969, except for one bend test at 0.076 cm.(0.030 in.) thickness. Further metallographic evaluation of each heat at each gauge subsequent to recrystallization heat treatment revealed a substantially uniform structure of large grains similar to those of typical TD Nickel Chromium sheet product. Therefore, it was concluded from this evaluation that there was no influence upon metallurgical behavior as a result of the roll-consolidation process. In addition, the investigation verified such anticipated advantages as improved yield, scheduling, and cost. For example, the yield at the intermediate gauge for Heats 3304 and 3305 were found to be 75.0% and 77.5% respectively in comparison to a comparable 60.0% for the forged route process

*All mechanical test values reported are for individual tests taken transverse to the rolling direction of the sheet unless otherwise noted.

(surface conditioning losses are not included in the aforementioned yields).

The four additional units for this phase of the investigation were hydrostatically compacted at 413.5 MN/m^2 (60,000 psi) and were identified as Heats 3285, 3280, 3282 and 3284. Each of these heats was subjected to the same set of process parameters as those used for the forged route billets so that an evaluation of material fabricated by both techniques could be carried out. The identical evaluation criteria employed for the forge route units was also employed for the roll-consolidation units.

Similar processing procedures to those previously described for Heats 3304 and 3305 were utilized for Heats 3285, 3280, 3282 and 3284. In addition, certain canning variables were utilized for the purpose of improving the decanned plate surface condition encountered during the roll consolidation exploration studies on Heats 3304 and 3305. These variables were assumed to have no interaction with other processing variables and also were assumed to have no influence on metallurgical characteristics of the materials under study.

Specifically, the canning variables employed the use of an aluminized steel*, Type 1, "slip sheet" between the TDNiCr compact and mild steel cover plate shown in Figure 14. This technique was believed to inhibit work-cover plate bonding and also permitted rolling in one can all the way to an intermediate gauge of 0.25 to 0.64 cm.(0.1 to 0.250 in.).

---

*Armco Aluminized Steel, Type 1, Armco Steel Corp.

TABLE 2.

MECHANICAL PROPERTIES OF ROLL CONSOLIDATED SHEET

Heat No.	Gauge cm.	Room Temperature UTS MN/m^2	Room Temperature YS MN/m^2	Room Temperature Elong. % cm.	1093C UTS MN/m^2	1093C YS MN/m^2	1093C Elong. % cm.	Stress Rupture @1093°C 37.90 MN/m^2	Trans. Bend Test
3304	0.102	846.1	583.6	24.0	126.8	111.6	3.0	>112.0	3T
3304	0.076	888.1	607.7	24.0	113.7	103.4	3.5	>112.0	3T
3304	0.051	790.3	500.2	22.5	124.0	124.0	2.5	> 91.5	2T
3304	0.036	776.5	603.6	23.0	112.3	77.2	3.0	> 93.3*	3T
3305	0.102	811.0	530.5	22.5	127.5	125.4	3.0	> 68.3	3T
3305	0.076	794.4	534.7	23.0	119.2	119.2	3.0	> 72.1	4T
3305	0.051	830.2	556.7	22.0	104.7	99.2	2.5	> 91.8	3T
3305	0.036	779.3	536.0	17.5	92.3	-	1.0	> 92.8	1.5T

*Tested at 27.6 MN/m^2

TABLE 2

MECHANICAL PROPERTIES OF ROLL CONSOLIDATED SHEET

Heat No.	Gauge in.	Room Temperature UTS ksi	Room Temperature YS ksi	Room Temperature Elong. % in.	2000°F UTS ksi	2000°F YS ksi	2000°F Elong. % in.	Stress Rupture @ 2000°F 5500 psi Hours	Trans. Bend Test
3304	0.040	122.8	84.7	24.0	18.4	16.2	3.0	>112.0	3T
3304	0.030	128.9	88.2	24.0	16.5	15.0	3.5	>112.0	3T
3304	0.020	114.7	72.6	22.5	18.0	18.0	2.5	> 91.5	2T
3304	0.014	112.7	87.6	23.0	16.3	11.2	3 0	> 93.3*	3T
3305	0.040	117.7	77.0	22.5	18.5	18.2	3.0	> 68.3	3T
3305	0.030	115.3	77.6	23.0	17.3	17.3	3.0	> 72.1	4T
3305	0.020	120.5	80.8	22.0	15.2	14.4	2.5	> 91.8	3T
3305	0.014	113.1	77.8	17.5	13.4	-	1.0	> 92.8	1.5T

*Tested at 4000 psi

The variables employed during this phase of the investigation are summarized in Table 3. One of the two heats incorporating the aluminized slip sheets, Heat 3282, was rolled all the way to the intermediate gauge, 0.25 cm.(0.1 in.), without decanning. Heat 3280 was decanned at a breakdown gauge of approximately 3.05 cm.(1.2 in.) in thickness, due to can failure. The cover plate fractured at the interface of the TDNiCr work and the mild steel edge border interface. The failure can be seen in Figure 16. Subsequent to decanning, it was noted that the TDNiCr slab surfaces were irregular as shown in Figure 17.

Examination of the cover plates and slip sheets indicated that the surface irregularities were initiated at the TDNiCr surface and transferred outwardly through the slip sheet and finally to the mild steel can. No assignable cause could be readily identified. However, the surface appearance on Heat 3282 did not exhibit this condition. It was therefore considered that rolling all the way to an intermediate gauge of 0.25 cm.(0.1 in.) with the aluminized steel slip sheet was effective in alleviating this condition. Heat 3280 was processed with one surface conditioned and one surface left in the unconditioned stage in an effort to determine effect of surface upon subsequent rolling. The slab was recanned and rolled to an intermediate gauge of 0.25 cm. (0.1 in.) thick using conventional rolling procedures. This plate was decanned and the surfaces examined. The unconditioned surface was found to be similar to those of Heats 3304 and 3305 at intermediate gauge. The conditioned surface was found to be free from any surface irregularities.

It may be noted in Table 3 that Heat 3284 had a starting powder weight of 35.88 kg.(79.1 lb.) instead of 45.36 kg.(100 lb.). This low weight was a result of the rubber boot folding in the compact during hydrostatic pressing. The depression caused by the fold can be seen in Figure 18. In order to correct the resultant defective compact, the center section containing the fold was removed by sawing as shown in Figure 18. The saw cut was made at approximately a 60° angle which was considered beneficial for bonding at the joint of the two end sections during subsequent roll consolidation.

After sawing, the two end sections were sintered and placed in a conventional roll consolidation can sized for the reduced weight and volume. The unit was then fabricated in a conventional manner. Evaluation of the join at 2.54 cm. (1.0 in.) and 0.25 cm.(0.1 in.) by metallographical techniques and mechanical properties indicated that a 100 percent metallurgical bond was achieved as a result of roll consolidation and subsequent fabrication.

This technique of joining during consolidation was quite encouraging since it would be readily adaptable to scale up procedures for multi-compact consolidation.

Again referring to Table 3, it may be noted that no yield data has been reported for Heat 3282 at conditioned sheet bar size; the reason being that decanning was purposely avoided at this stage of processing on this heat in order to roll directly to an intermediate gauge plate thickness.

TABLE 3

ROLL CONSOLIDATION ROUTE PROCESSING PARAMETERS AND YIELDS

Operation	HEAT NO. 3285	3280	3282	3284
Starting Powder Weight kg.	45.36	45.36	45.36	35.88
Sinter Temp.	954°C	1066°C	954°C	1066°C
Consolidation Method	Rolling	Rolling	Rolling	Rolling
Consolidation Temp.	1010°C	1010°C	1066°C	1066°C
Conditioned Sheet Bar Size	2.40x 57.79x 30.48 cm.	2.65x 34.29x 47.94 cm.	-	2.44x44.45x 24.21 cm.
Conditioned Weight kg.	35.39	35.74	-	26.44
Roll Consolidated Sheet Bar Yield	78.0%	78.8%	-	74.0%
Post Consolidation H.T.	1010°C	None	1066°C	None
Breakdown Rolling Temp.	1010°C	1010°C	1066°C	1066°C
Decan Gauge	2.54 cm.	2.54 cm.	0.38 cm.	2.54 cm.
Yield After Trim at Decan Gauge	66.2%	61.0%	82.1%	53.5%
Aluminized Slip Sheet	No	Yes	Yes	No

TABLE 3

ROLL CONSOLIDATION ROUTE PROCESSING PARAMETERS AND YIELDS

Operation	HEAT NO. 3285	3280	3282	3284
Starting Powder Weight lb.	100.0	100.0	100.0	79.1
Sinter Temp.	1750°F	1950°F	1750°F	1950°F
Consolidation Method	Rolling	Rolling	Rolling	Rolling
Consolidation Temp.	1850°F	1850°F	1950°F	1950°F
Conditioned Sheet Bar Size	.945" x 22-3/4"x12"	1.043" x 13-1/2"x 18-7/8"	-	.960" x 17-1/2"x 11-1/2"
Conditioned Weight Lbs.	78.0	78.8	-	58.3
Roll Consolidated Sheet Bar Yield	78.0%	78.8%	-	74.0%
Post Consolidation H.T.	1850°F	None	1950°F	None
Breakdown Rolling Temp.	1850°F	1850°F	1950°F	1950°F
Decan Gauge	1.0	1.0	0.15	1.0
Yield after Trim at Decan Gauge	66.2%	61.0%	82.1%	53.5%
Aluminized Slip Sheet	No	Yes	Yes	No



FIGURE 16

ROLL CONSOLIDATED TDNiCr SLAB (HEAT 3280)

ROLLED TO 3.05 cm.(1.2 in.)



FIGURE 17

SURFACE IRREGULARITIES

IN DECANNED ROLL CONSOLIDATED TDNiCr SLAB (HEAT 3280)

AT 3.05 cm.(1.2 in.)

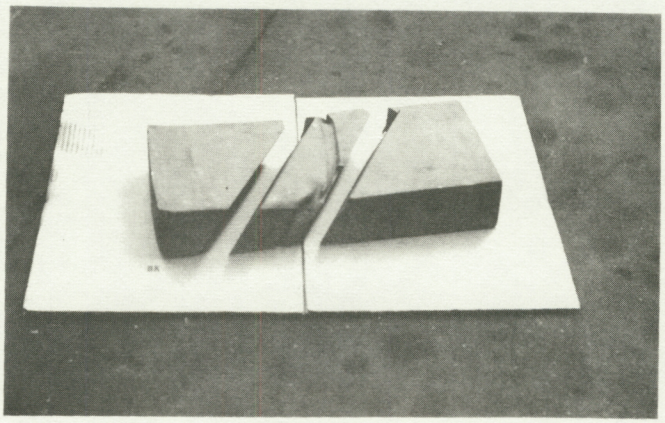


FIGURE 18

DEFECTIVE COMPACTION OF TDNiCr (HEAT 3284)

CENTER SECTION REMOVED BY SAWING

As in the case of forged sheet bars, no great change of yield at either conditioned sheet bar stage or at decanned gauge plate may be attributed to sintering temperatures and/or consolidation temperature of the roll consolidated sheet bars. It should be noted, however, that the yields at 2.54 cm.(1.0 in.) thickness for roll consolidation are greater than yields for forged sheet bar at a thicker conditioned size, e.g. 3.81 cm.(1.5 in.).

(3.) Consolidation Study Evaluation

The evaluation criteria employed for the consolidation studies carried out during this phase of the program included the following:

Sheet bar yields
Edge cracking
Breakdown plate yields
Sheet yields
Sheet properties vs. gauge
Chromium oxide and thoria parameters in plate and sheet

The data are summarized in Table 4 for the ten - 45.36 kg.(100 lb.) units.

- Sheet Bar Yields

  Sheet bar yields were determined by computing the cumulative percentage of material contained in a final conditioned slab.

  It may be noted in Table 4 that the cumulative yields for those heats consolidated

TABLE 4

CONSOLIDATION STUDY EVALUATION

	3279	3281	3283	3278	3304	3305	3285	3280	3282	3284
Start Powder Wt. kg.	45.36	45.36	45.36	40.84	44.68	45.36	45.36	45.36	45.36	35.80
Sinter Temp.	954°C	1066°C	954°C	1066°C	954°C	954°C	954°C	1066°C	954°C	1066°C
Consol. Method	Forge	Forge	Forge	Forge	Roll	Roll	Roll	Roll	Roll	Roll
Consol. Temp.	1010°C	1010°C	1066°C	1066°C	1010°C	1010°C	1010°C	1010°C	1066°C	1066°C
	Thickness 3.81 cm. Sheet Bar						Thickness 2.54 cm. Sheet Bar			
Cond. Wt. kg.	32.70	32.16	34.34	29.44	-	-	35.39	35.44	-	26.44
Yield	72.1%	72.5%	75.7%	72.0%	-	-	78.0%	78.8%	-	74.0%
Breakdown Roll Temp. to 2.54 cm.	1010°C	1010°C	1066°C	1066°C	1010°C	1010°C	1010°C	1010°C	1066°C	1066°C
Yield at ~.254 cm.	56.5%	58.4%	60.8%	57.4%	75.0%	77.5%	66.2%	61.0%	82.1%	53.5%
ThO_2 Size Before Rx @.102 cm.	14.5mμ	14.5mμ	14.5mμ	16.5mμ	14.0mμ	15.5mμ	15.5mμ	18.5μ	19.0mμ	19.5mμ

TABLE 4

CONSOLIDATION STUDY EVALUATION

	3279	3281	3283	3278	3304	3305	3285	3280	3282	3284
Start Powder Wt. lb.	100.0	100.0	100.0	90.0	98.5	100.0	100.0	100.0	100.0	79.1
Sinter Temp.	1750°F	1950°F	1750°F	1950°F	1750°F	1750°F	1750°F	1950°F	1750°F	1950°F
Consol. Method	Forge	Forge	Forge	Forge	Roll	Roll	Roll	Roll	Roll	Roll
Consol. Temp.	1850°F	1850°F	1950°F	1950°F	1850°F	1850°F	1850°F	1850°F	1950°F	1950°F
	Thickness 1.5" Sheet Bar						Thickness 1.0" Sheet Bar			
Cond. Weight lb.	72.1	72.5	75.7	64.9	-	-	78.0	78.8	-	58.3
Yield	72.1%	72.5%	75.7%	72.0%	-	-	78.0%	78.8%	-	74.0%
Breakdown Roll Temp. to 1"	1850°F	1850°F	1950°F	1950°F	1850°F	1850°F	1850°F	1850°F	1950°F	1950°F
Yield at ~.100"	56.5%	58.4%	60.8%	57.4%	75.0%	77.5%	66.2%	61.0%	82.1%	53.5%
ThO_2 Size Before Rx @ .040"	14.5mμ	14.5mμ	14.5mμ	16.5mμ	14.0mμ	15.5mμ	15.5mμ	18.5mμ	19.0mμ	19.5mμ

TABLE 4 (CONT'D.)

CONSOLIDATION STUDY EVALUATION

	3279	3281	3283	3278	3304	3305	3285	3280	3282	3284
ThO_2 Size after Rx @.102 cm.	26.5mμ	28.5mμ	26.5mμ	22.0mμ	26.0mμ	20.0mμ	20.0mμ	22.0mμ	23.5mμ	21.0mμ
Room Temperature Properties at 0.102 cm. Ga.										
UTS MN/m^2	822.6	822.6	833.0	800.6	846.0	742.0	828.9	847.5	918.4	831.6
YS MN/m^2	562.9	530.5	545.7	558.8	583.6	530.5	543.6	575.3	695.9	544.3
Elong. %	27.1	27.1	27.0	25.0	24.0	22.5	25.0	25.0	25.0	25.0
1093°C Temperature Properties at 0.102 cm. Ga.										
UTS MN/m^2	106.1	107.4	112.3	106.1	126.8	127.5	120.5	115.0	115.8	108.2
YS MN/m^2	103.4	106.8	111.6	99.2	111.6	125.4	118.5	113.7	114.4	106.1
Elong. %	6.0	6.0	6.0	7.5	3.0	3.0	7.0	4.5	7.5	7.5
1093°C Stress Rupture at 37.9 NM/m^2 for 0.102 cm.										
Hours	(Exceeded 20 hours in all cases)									
Transverse Bend at 0.102 cm. Ga.										
	3T	3T	2.5T	2.5T	3T	3T	4T	3T	3T	3T
Room Temperature Properties at 0.051 cm.										
UTS MN/m^2	830.9	808.9	739.3	818.8	790.3	830.2	784.1	788.9	848.2	803.4
YS MN/m^2	547.0	578.0	498.1	545.7	500.2	556.7	523.0	516.1	641.5	522.1
Elong. %	22.5	26.0	22.5	24.5	22.5	22.0	25.0	27.1	25.0	25.0

TABLE 4 (CONT'D.)

CONSOLIDATION STUDY EVALUATION

	3279	3281	3283	3278	3304	3305	3285	3280	3282	3284
ThO_2 Size after Rx @ .040"	26.5mμ	28.5mμ	26.5mμ	22.0μ	26.0mμ	20.0mμ	20.0mμ	22.0mμ	23.5mμ	21.0mμ
Room Temperature Properties at 0.040" Ga.										
UTS ksi	119.4	119.4	120.9	116.2	122.8	117.7	120.3	123.0	133.3	120.7
YS ksi	81.7	77.0	79.2	81.1	84.7	77.0	78.9	83.5	101.0	79.0
Elong. %	27.1	27.1	27.0	25.0	24.0	22.5	25.0	25.0	25.0	25.0
2000°F Temperature Properties at 0.040" Ga.										
UTS ksi	15.4	15.6	16.3	15.4	18.4	18.5	17.5	16.7	16.8	15.7
YS ksi	15.0	15.5	16.2	14.4	16.2	18.2	17.2	16.5	16.6	15.4
Elong. %	6.0	6.0	6.0	7.5	3.0	3.0	7.0	4.5	7.5	7.5
2000°F Stress Rupture at 5500 psi for 0.040" Ga.										
Hours	(Exceeded 20 hours in all cases)									
Transverse Bend at 0.040" Ga.	3T	3T	2.5T	2.5T	3T	3T	4T	3T	3T	3T
Room Temperature Properties at 0.020" Ga.										
UTS ksi	120.6	117.4	107.3	118.5	114.7	120.5	113.8	114.5	123.1	116.6
YS ksi	79.4	83.9	72.3	79.2	72.6	80.8	75.9	74.9	93.1	76.5
Elong. %	22.5	26.0	22.5	24.5	22.5	22.0	25.0	27.1	25.0	25.0

TABLE 4 (CONT'D.)

CONSOLIDATION STUDY EVALUATION

	3279	3281	3283	3278	3304	3305	3285	3280	3282	3284
1093°C Temperature Properties at 0.051 cm. Ga.										
UTS MN/m^2	99.2	113.7	108.6	114.4	124.0	104.7	119.9	111.6	110.9	111.6
YS MN/m^2	99.2	108.2	108.9	109.6	124.0	99.2	119.9	111.6	110.9	105.4
Elong. %	4.0	6.0	2.5	6.0	2.5	2.5	7.0	6.0	5.0	5.0
1093°C Stress Rupture at 37.9 MN/m^2 for 0.051 cm. Ga.										
Hours	(Exceeded 20 hours in all cases)									
Transverse Bend at 0.051 cm.										
	1.5T	1.5T	1.5T	2T	2T	3T	<1T	2T	2T	2T

TABLE 4 (CONT'D.)

CONSOLIDATION STUDY EVALUATION

	3279	3281	3283	3278	3304	3305	3285	3280	3282	3284
2000°F Temperature Properties at 0.020" Ga.										
UTS ksi	14.4	16.5	15.8	16.6	18.0	15.2	17.4	16.2	16.1	16.2
YS ksi	14.4	15.7	15.8	15.9	18.0	14.4	17.4	16.2	16.1	15.3
Elong. %	4.0	6.0	2.5	6.0	2.5	2.5	7.0	6.0	5.0	5.0
2000°F Stress Rupture at 5500 psi for 0.020" Ga.										
Hours	(Exceeded 20 hours in all cases)									
Transverse Bend at 0.020" Ga.										
	1.5T	1.5T	1.5T	2T	2T	3T	>1T	2T	2T	2T

by forging ranged from 72.0 to 75.7 percent. The few percent differences that do occur appear to be typical process variances and would therefore be considered insignificant. Accordingly, these yield differences should not be attributed to sintering and/or consolidation temperature variables.

Of the six heats consolidated by rolling, three (3304, 3305 and 3282) show no yields reported at the conditioned slab stage of processing, while the remaining three (3285, 3280 and 3284) have cumulative yields at conditioned slab size ranging from 74.0 to 78.8 percent. The former three heats indicate no yields at this stage since they were rolled directly to intermediate gauge plate omitting the decanning - conditioning step at the 2.54 cm.(1.00 in.) thickness. As in the case of the forged - conditioned slabs, roll consolidated heats (3285, 3280 and 3284) exhibited insignificant yield differences thus eliminating sintering and/or consolidation temperatures as an effect upon conditioned - slab yields.

However, comparing yields of forged - conditioned slabs with those rolled and conditioned, it may be noted that the roll consolidation

yields are not only greater, but greater at an approximate 30 percent reduced thickness thus making the yield improvement even more significant.

- Edge Cracking

  Edge cracking at decanned sheet bar or decanned intermediate gauge plate could not be correlated with any of the variables investigated. It appeared that edge cracking might be affected by piece and can configuration and initial consolidation mechanics.

  Any difference in edge cracking that could be attributed to process route parameters was not easily detected. Therefore, it should be considered as one of the factors reflected in either conditioned slab yields or intermediate gauge plate yields.

- Breakdown Plate Yields

  Again referring to Table 4, it may be noted that intermediate gauge plate yields, 0.25 cm. (0.1 in.), of the four forged heats are quite consistant and range between 56.5 and 60.8 percent. As in the case of conditioned slab yields, the slight differences that do occur appear to be typical process variances and therefore are considered insignificant.

On the other hand, the six roll consolidated heats vary over quite a wide spread and range from 53.5 to 82.1 percent. Evaluating the data as presented in Table 4, it is seen that Heats 3304, 3305 and 3282 exhibit the highest yields. The reason for this improved yield is the omission of the decanning and conditioning step at the 2.54 to 3.81 cm. (1 to 1.5 in.) processing step. This may be readily observed by the decreased yields exhibited by Heats 3285, 3280 and 3284.

The extremely low yield of Heat 3284 at intermediate gauge plate stage was attributed to its less than usual compact weight of 35.88 kg.(79.1 lbs.) as compared to approximately 45.36 kg.(100 lbs.) for the balance of the units. Since yield losses occurring between conditioned slab stage of 2.54 cm. (1.0 in.) and intermediate gauge plate of 0.25 cm.(0.1 in.) are caused primarily by edge cracking and plate loss at "tails", the amount of material lost is relatively constant, but in the case of a lighter weight unit, the percent loss is greater.

In summary, it was shown that intermediate gauge plate yields were most likely not related to sintering and/or consolidation temperature variables as practiced during this program.

However, yields were shown to be slightly improved as a result of roll consolidation with a decanning and conditioning step at the 2.54 to 3.81 cm.(1.0 to 1.5 in.) thickness as compared to the forged route process. Further, a quite significant improvement in yield at intermediate gauge plate thickness was effected as a result of the roll consolidation process coupled with the omission of the decanning-conditioning step at 2.54 to 3.81 cm.(1.0 to 1.5 in.) thickness.

- Sheet Yields

Since only approximately one quarter of each of the heats evaluated during the consolidation studies was processed into finished sheet at 0.051 and 0.102 cm.(0.020 and 0.040 in.) gauge sheet for test purposes, no sheet yields were attainable. In addition, the balance of the material will be utilized for other investigations of this contract thus eliminating the ability to determine sheet yields.

It is believed however, that sheet yields would follow the same trends established at decanned-conditioned slab thickness and intermediate gauge plate thickness of the forge route and roll consolidation processes.

- Sheet Properties vs. Gauge

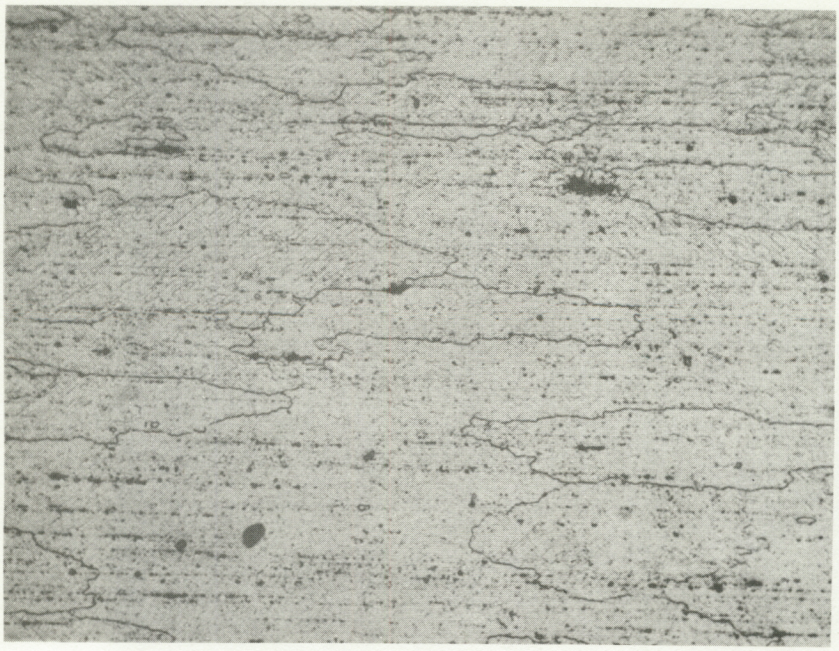
  Approximately one quarter of each of the ten heats fabricated to intermediate gauge plate during this investigation was finish rolled to 0.051 and 0.102 cm.(0.020 and 0.040 in.) sheet, recrystallize heat treated and then submitted to mechanical testing at room temperature and 1093°C (2000°F) and metallographical evaluation.

  Referring to Table 4, it is evident that no significant difference appeared in sheet properties at either 0.102 cm.(0.040 in.) or 0.051 cm.(0.020 in.) gauges as a result of processing parameters. Further, the results from these tests indicated that not only properties but metallurgical structure as well was quite typical of TDNiCr sheet fabricated prior to the initiation of this contract.

  Photomicrographs of typical structures obtained by both the forged route and roll consolidation route are shown in Figure 19 and Figure 20.

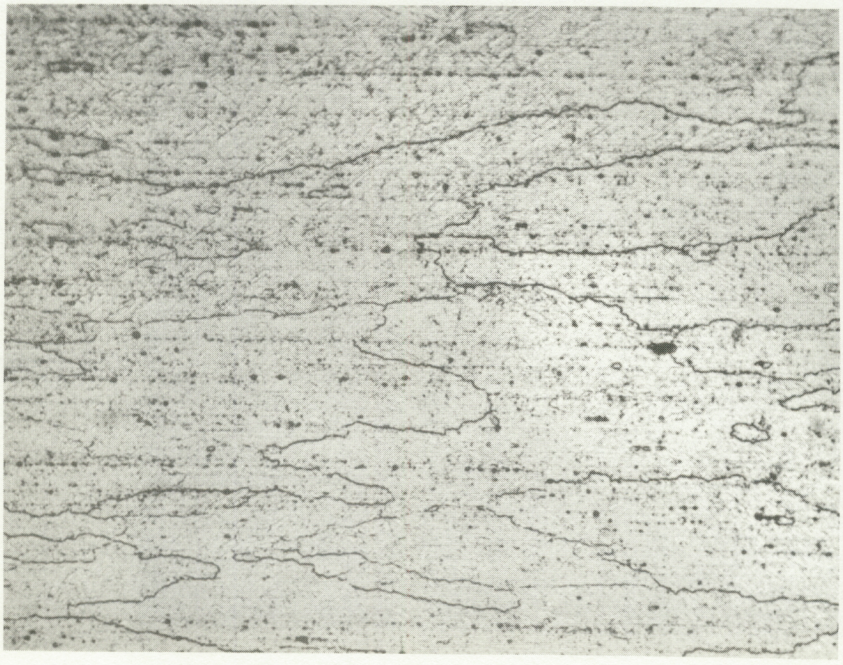
- Chromium Oxide and Thoria Parameters in Plate and Sheet

  A metallographic evaluation for chromium oxide content and distribution was carried out on all ten heats fabricated during the consolidation



LONGITUDINAL

0.102 cm.(0.040 in.) SHEET



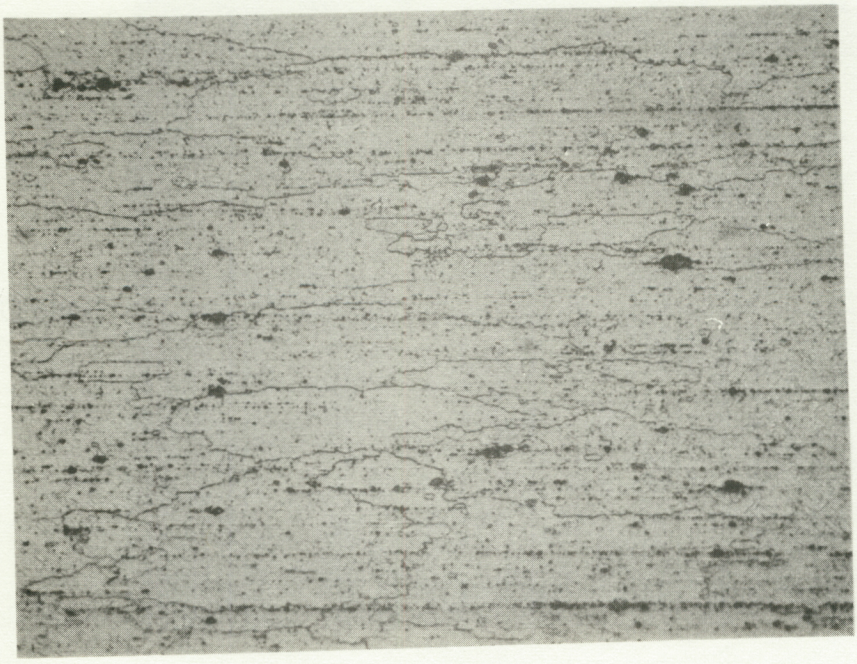
LONGITUDINAL

0.051 cm.(0.020 in.) SHEET

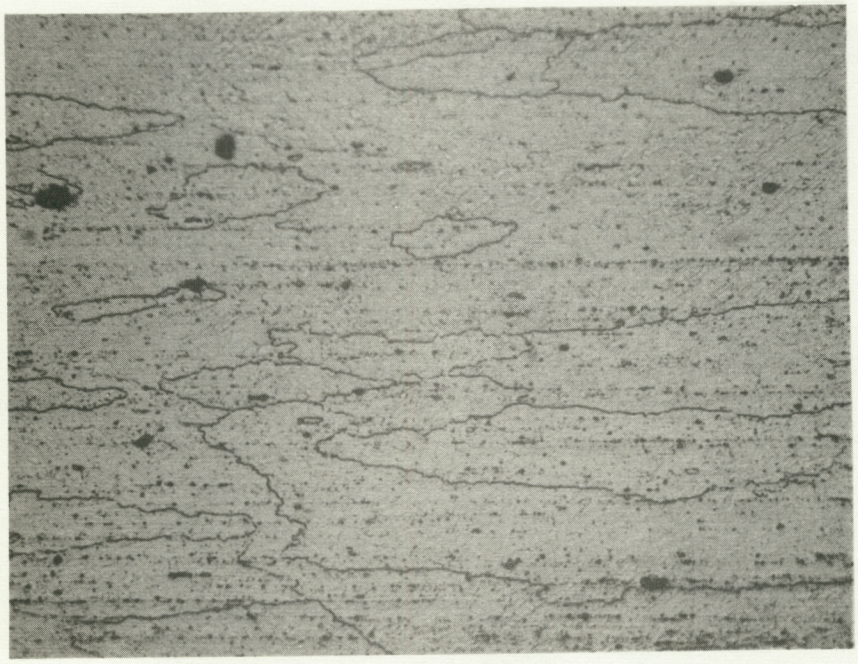
Specimens Recrystallized & Etched with Nital. 250X

FIGURE 19

TYPICAL TDNiCr SHEET MICROSTRUCTURE - FORGED ROUTE PROCESS



LONGITUDINAL



LONGITUDINAL

0.051 cm.(0.020 in.) SHEET

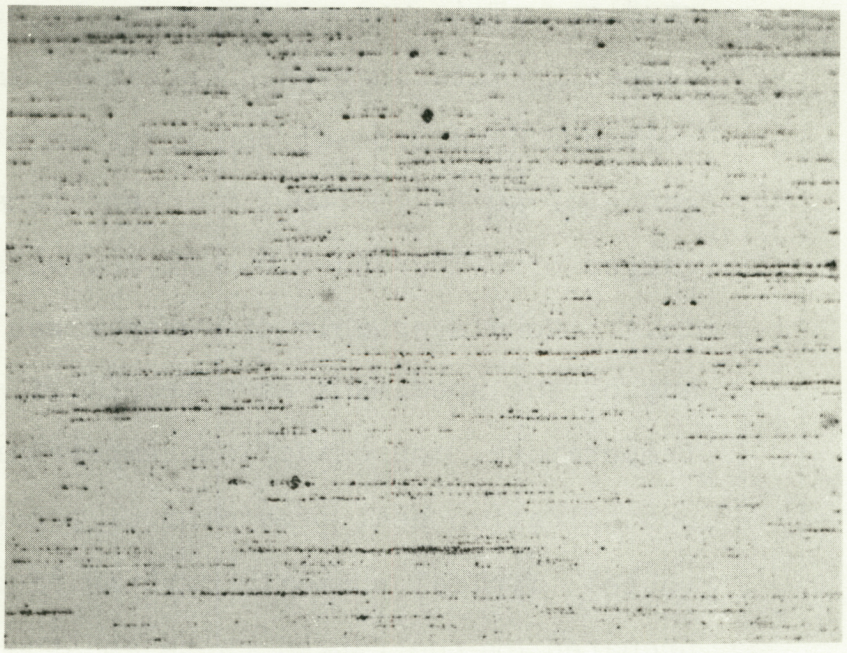
Specimens Recrystallized & Etched with Nital. 250X

FIGURE 20

TYPICAL TDNiCr SHEET MICROSTRUCTURE - ROLL CONSOLIDATION PROCESS

studies. This was accomplished by means of comparing metallographic specimens in the as-polished condition at the intermediate plate gauge of ~0.25 cm.(~0.1 in.) and final sheet gauges of 0.102 and 0.051 cm.(0.040 and 0.020 in.). No discernable difference was noted in any of the specimens as a result of sintering temperature, consolidation temperature, post consolidation heat treatment or process route. Typical photomicrographs of specimens prepared by the forged route and the roll consolidation route showing comparable chromium oxide distribution may be noted in Figures 21 and 22.

Referring to Table 4, it should also be pointed out that no difference in thoria size was indicated as a result of sintering temperature, consolidation temperature, post consolidation heat treatment or process route. Based upon these findings, additional work was carried out in an effort to determine the upper temperature limitation on sintering and/or consolidation operations that will not have a detrimental effect on sheet properties as a result of excessive thoria growth. Results of this work are discussed in the following text.



LONGITUDINAL

0.25 cm.(0.1 in.) PLATE



TRANSVERSE

0.25 cm.(0.1 in.) PLATE

Specimens Heat Treated, as Polished. 250X

FIGURE 21

TYPICAL Cr_2O_3 DISTRIBUTION AT 0.25 cm.(0.1 in.)
INTERMEDIATE GAUGE - FORGED ROUTE PROCESS



LONGITUDINAL



TRANSVERSE

(4.) Exploration of Breakdown Rolling Practice

The process parameters of sintering temperature and consolidation temperature appeared to have little effect on the metallurgical structures and properties of TDNiCr sheet when rolled to product. Consequently, process yields and economics become the determining factors in choosing the process sequences. Roll consolidation produced higher yields than forging and has the potential for even higher yield.

In order to determine the best consolidation and breakdown rolling practice, five additional 45.36 kg.(100 lb.) units were prepared for the optimization investigation shown in the Modified Flow Chart, Figure 3. The process variables are given in Table 5. Sinter temperature was kept constant at 954°C(1750°F).

One rolling experiment which is not apparent from Table 5 was an attempt to warm roll to gauge without a mild steel can. Billet 3354 was roll consolidated and hot rolled at 1010°C (1850°F) to 2.54 cm.(1.0 in.) and decanned. The slab was conditioned by machining and grinding, Figure 23, to provide the best possible shape for rolling. Rolling to 0.25 cm.(0.1 in.) intermediate gauge plate was attempted at 760°C(1400°F). Even though a reduction of 18% was attained, the workpiece alligatored badly on the first rolling pass, Figure 24. Thus despite excellent slab quality it does not appear feasible to warm roll TDNiCr bare at 2.54 cm. (1.0 in.) thickness.

Heats 3355 and 3357 were rolled at 1010°C and 1066°C(1850° and 1950°F) respectively down to 1.27 cm.(0.5 in.)

rather than 2.54 cm.(1.0 in.) as has been practiced. Since the finish gauges of material for this program are 0.051 and 0.102 cm. (0.020 and 0.040 in.), process economics and yields were felt to be enhanced by greater quantities of hot work. Heats 3356 and 3358 were run in an effort to reproduce the results obtained in rolling to 0.25 cm.(0.1 in.) decan gauge in the initial 10 - 45.36 kg.(100 lb.) units previously described.

The results of this work indicated that additional hot work introduced to the process as shown for Heats 3355 and 3357 tended to decrease edge cracking and improve yields at 0.25 cm. (0.10 in.) thickness. At the same time, properties of finished sheet shown in Table 6 were found to be comparable to sheet rolled by standard processing.

Yields on Heats 3355, 3356, 3357 and 3358 were lower than anticipated, primarily as a result of poor surface which appeared similar in nature to that previously encountered on Heats 3304 and 3305. In particular Heat 3358 did not reproduce results previously obtained by Heat 3282 using the identical processing procedures.

The rolling behavior and yield results from the series of billets were not conclusive. In order to further define the breakdown rolling practice the following changes were made in the original Flow Chart Figure 2.

- The reproducibility series of billets was reduced from five to three billets.

TABLE 5

BREAKDOWN ROLLING PRACTICE

	3354	3355	3356	3357	3358
Sinter Temp.	954°C	954°C	954°C	954°C	954°C
Consolidation Method	Roll	Roll	Roll	Roll	Roll
Al. Steel Slip Sheet	x	x	x	x	x
Consolidation Temp.	1010°C	1010°C	1010°C	1066°C	1066°C
Breakdown Roll Temp.	1010°C	1010°C	1010°C	1066°C	1066°C
Gauge	2.54 cm.	1.27 cm.	2.54 cm.	1.27 cm.	2.54 cm.
Decan Gauge	2.54 cm.	0.254 cm.	0.254 cm.	0.254 cm.	0.254 cm.

TABLE 5

BREAKDOWN ROLLING PRACTICE

	3354	3355	3356	3357	3358
Sinter Temp.	1750°F	1750°F	1750°F	1750°F	1750°F
Consolidation Method	Roll	Roll	Roll	Roll	Roll
Al. Steel Slip Sheet	x	x	x	x	x
Consolidation Temp.	1850°F	1850°F	1850°F	1950°F	1950°F
Breakdown Roll Temp.	1850°F	1850°F	1850°F	1950°F	1950°F
Gauge	1.0"	0.5"	1.0"	0.5"	1.0"
Decan Gauge	1.0"	0.1"	0.1"	0.1"	0.1"

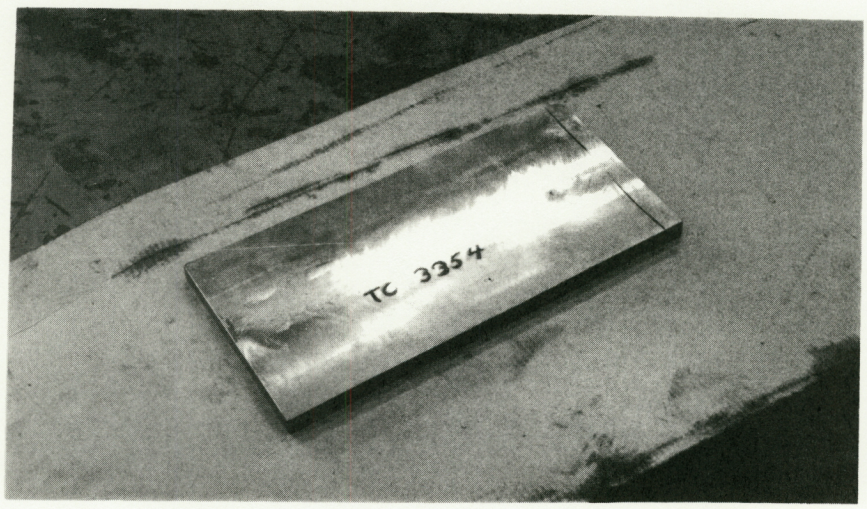


FIGURE 23

CONDITIONED 2.54 cm.(1 in.) TDNiCr SLAB
(HEAT 3354)

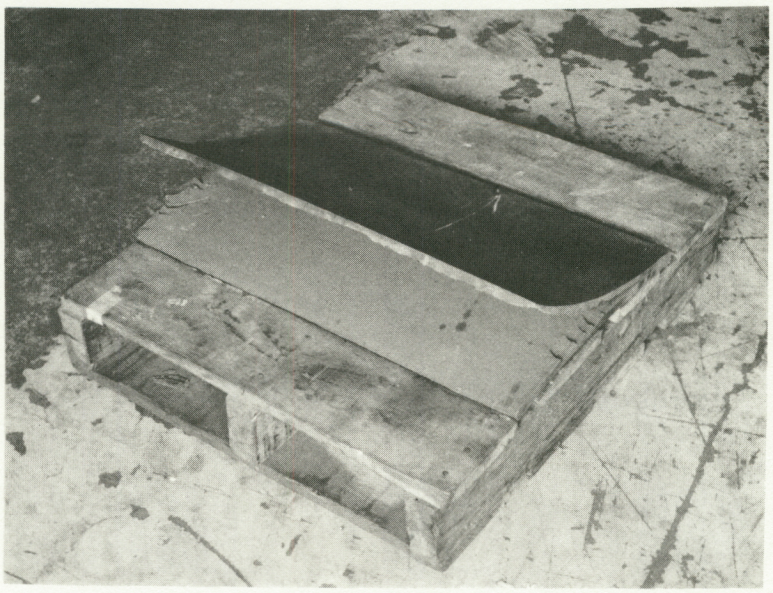


FIGURE 24

FAILURE OF WARM ROLLED PLATE (HEAT 3354)

ROLLED BARE

(ONE PASS AT 760°C(1400°F) - 18% REDUCTION)

TABLE 6

PROPETIES OF TDNiCr SHEET FROM ROLLING STUDY

	3355	3356	3357	3358
.040 in. R.T.				
UTS ksi	119.5	124.3	141.7	115.7
YS ksi	89.4	86.6	117.2	83.1
El. %	25.0	21.5	12.0	21.4
.040 in. 2000°F				
UTS ksi	19.4	21.9	20.2	19.9
YS ksi	19.3	21.3	20.2	19.4
El. %	5.5	5.0	7.0	5.5
.040 in. Stress Rupture	Exceeded 20 hours in all cases			
.020 in. R.T.				
UTS ksi	120.5	107.3	120.7	114.4
YS ksi	105.6	87.3	87.7	79.5
El. %	20.0	14.5	19.5	18.0
.020 in. 2000°F				
UTS ksi	17.7	17.2	18.4	17.5
YS ksi	17.7	17.2	18.2	17.0
El. %	6.0	4.0	6.5	2.0
.020 in. Stress Rupture	Exceeded 20 hours in all cases			
Thoria Size mμ Before Rx	13.5 @ .145 in.	12.0 @ .240 in.	13.5 @ .150 in.	13.0 @ .250 in.
Thoria Size mμ After Rx	19.5 @ .040 in.	21.0 @ .040 in.	24.0 @ .040 in.	29.0 @ .040 in.
Yield *%	68.5% @ .145 in.	70.5% @ .240 in.	88.2% @ .150 in.	77% @ .250 in.

*All had poor surfaces; the yield calculations do not include this factor.

TABLE 6

PROPERTIES OF TDNiCr SHEET FROM ROLLING STUDY

	3355	3356	3357	3358
0.102 cm. R.T.				
UTS - MN/m^2	823.4	856.4	976.3	797.2
YS - MN/m^2	616.0	596.7	807.5	572.6
El. %	25.0	21.5	12.0	21.4
0.102 cm. 1093°C				
UTS - MN/m^2	133.7	151.0	139.2	137.1
YS - MN/m^2	133.0	146.8	139.2	133.7
El. %	5.5	5.0	7.0	5.5
0.102 cm. Stress Rupture	Exceeded 20 hours in all cases			
0.051 cm. R.T.				
UTS - MN/m^2	830.2	739.3	831.6	788.2
YS - MN/m^2	727.6	601.5	604.3	547.8
El. %	20.0	14.5	19.5	18.0
0.051 cm. 1093°C				
UTS - MN/m^2	122.0	118.5	126.8	120.6
YS - MN/m^2	122.0	118.5	125.4	117.1
El. %	6.0	4.0	6.5	2.0
0.051 cm. Stress Rupture	Exceeded 20 hours in all cases			
Thoria Size mμ Before Rx	13.5 @ 0.37 cm.	12.0 @ 0.61 cm.	13.5 @ 0.38 cm.	13.0 @ 0.64 cm.
Thoria Size mμ After Rx	19.5 @ 0.102 cm.	21.0 @ 0.102 cm.	24.0 @ 0.102 cm.	29.0 @ 0.102 cm.
Yield*%	58.5 @ 0.37 cm.	70.5 @ 0.61 cm.	88.2 @ 0.38 cm.	77.0 @ 0.64 cm.

*All had poor surfaces; the yield calculations do not include this factor.

- Six production billets were used to help define the breakdown rolling parameters. These parameters have essentially no effect on metallurgical properties and hence do not endanger the quality of the production sheet. The changes are noted on the Modified Flow Chart, Figure 3. A total of eight billets were used to establish the rolling parameters; the primary variables being hot rolling temperature, canning practice and decanning practice. The specific processing parameters evaluated during this phase of the program are summarized in Table 7. These included breakdown rolling temperatures of 1010° and 1066°C (1850° and 1950°F), decanning gauges of 2.54 and 0.25 cm.(1.0 and 0.1 in.) in thickness and roll consolidation can cover plate thickness of either 0.32 or 0.63 cm.(1/8 or 1/4 in.).

  Reproducibility of results was not attained. Although the yields at intermediate gauge plate varied from 40 to 79%, no definite correlation could be established between any particular processing parameter or group of parameters and surface condition after decanning at 2.54 or 0.25 cm.(1.0 or 0.1 in.) thickness.

Figures 25, 26 and 27 show various degrees of surface irregularities on 2.54 cm.(1.0 in.) thick decanned sheet bars. Extent of surface roughness was judged by the amount of material removed from each face for cleanup. Thicknesses after cleanup are shown in Table 7 under the column headed "Decan Gauge-Slab". The general range of cleanup necessary appeared to vary from 0.127 to 0.32 cm.(0.050 to 0.125 in.) per face.

Surface conditions of heats processed directly to 0.25 cm.(0.1 in.) thick intermediate gauge plate were also quite inconsistent in appearance. Heats 3393, 3394 and 3385 had irregular surfaces similar in appearance to Heats 3304 and 3305. Heat 3387, however, fabricated in an identical manner to Heat 3385 had an excellent surface subsequent to decanning at the intermediate gauge plate step of processing.

Based upon the results obtained from these studies the most conservative processing sequence was chosen for use on the reproducibility series of billets and for all subsequent production billets.

TABLE 7

OPTIMIZATION OF ROLLING PRACTICE

Heat	Sinter Temp.	Cover Plate 0.32 cm.	Cover Plate 0.64 cm.	Consolidation and Rolling Temp.	Decan Gauge Conditioned Rolled Slab	Decan Gauge Inter. Gauge Plate	Yield % Slab	Yield % Inter. Gauge Plate	Decanned Surface Poor	Decanned Surface Fair	Decanned Surface Good
3384	954°C	x		1010°C	2.02 cm.	0.64 cm.	49.9	40.6	x		
3386	954°C	x		1010°C	2.35 cm.	0.28 cm.	70.8	56.4		x	
3393	954°C		x	1010°C		0.46 cm.		75.5	x		
3394	954°C		x	1010°C		0.42 cm.		79.0	x		
3382	954°C	x		1066°C	2.38 cm.	0.31 cm.	69.0	53.6		x	
3383	954°C	x		1066°C	2.22 cm.	0.30 cm.	60.8	50.1	x		
3385	954°C	x		1066°C		0.41 cm.		45.0	x		
3387	954°C	x		1066°C		0.47 cm.		78.9			x

TABLE 7

OPTIMIZATION OF ROLLING PRACTICE

Heat	Sinter Temp.	Cover Plate 1/8	Cover Plate 1/4	Consolidation & Rolling Temp.	Decan Gauge Conditioned Rolled Slab	Decan Gauge Inter. Gauge Plate	Yield % Slab	Yield % Inter. Gauge Plate	Decanned Surface Poor	Decanned Surface Fair	Decanned Surface Good
3384	1750°F	x		1850°F	.793"	.251"	49.9	40.6	x		
3386	1750°F	x		1850°F	.925"	.112"	70.8	56.4		x	
3393	1750°F		x	1850°F		.180"		75.5	x		
3394	1750°F		x	1850°F		.162"		79.0	x		
3382	1750°F	x		1950°F	.938"	.123"	69.0	53.6		x	
3383	1750°F	x		1950°F	.875"	.118"	60.8	50.1	x		
3385	1750°F	x		1950°F		.160"		45.0	x		
3387	1750°F	x		1950°F		.187"		78.9			x

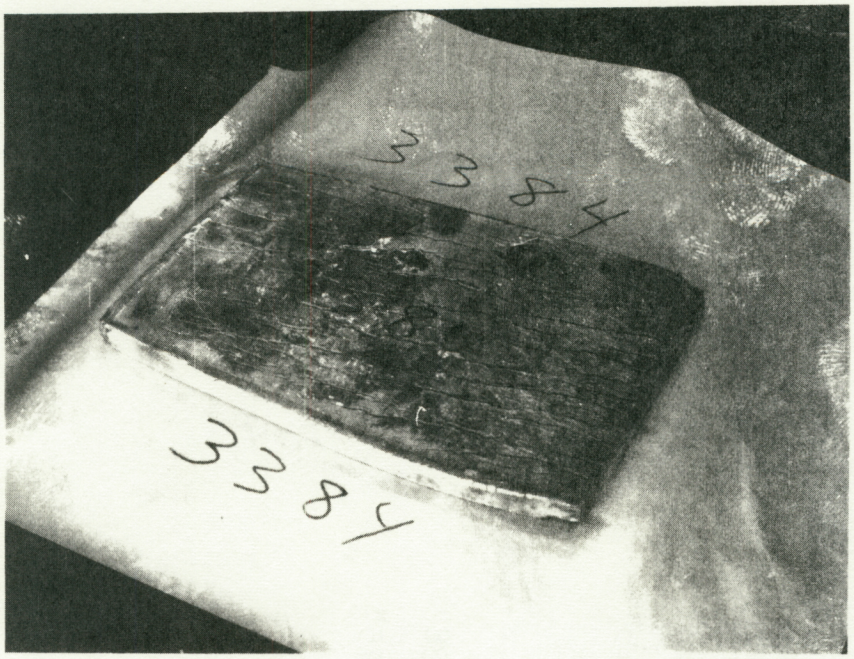


FIGURE 25

SURFACE OF DECANNED SLAB (HEAT 3384)

ROLL CONSOLIDATED AT 1010°C(1850°F)

[SURFACE REMOVAL REQUIRED - 0.31 cm.(0.125 in.)]



FIGURE 26

SURFACE OF DECANNED SLAB (HEAT 3386)

ROLL CONSOLIDATED AT 1010°C(1850°F)

[SURFACE REMOVAL REQUIRED 0.127 cm.(0.050 in.)]

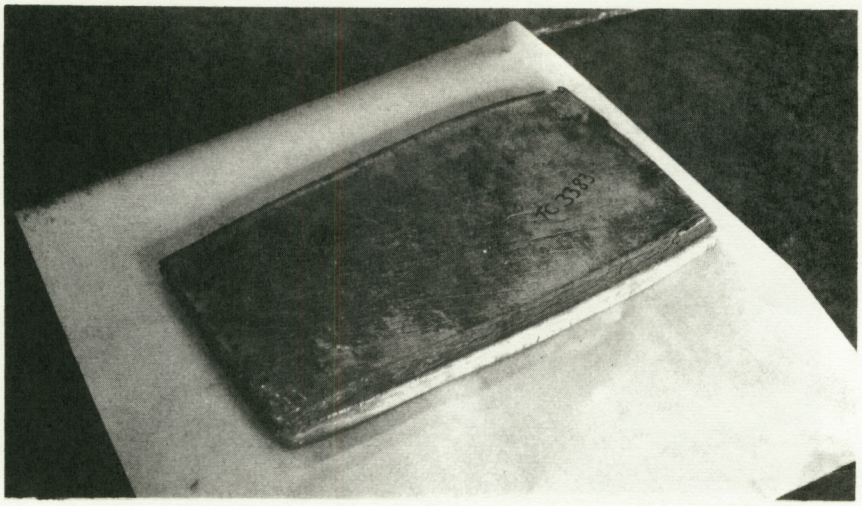


FIGURE 27

SURFACE OF DECANNED SLAB (HEAT 3383)

ROLL CONSOLIDATED AT 1066°C(1950°F)

[SURFACE REMOVAL REQUIRED - 0.229 cm.(0.090 in.)]

The process sequence is as follows:

- Compaction - Rubber Boot, No Mylar Liner
- Sinter - 954° C(1750° F)
- Consolidation Method - Roll Consolidation
- Consolidation Temperature - 1010° C(1850° F)
- Can - Aluminized Steel Slip Sheet
  0.32 cm.(1/8 in.) Thick Cover Plates
- Breakdown rolling temperature - 1010° C(1850° F)
- Decan gauge - 2.54 cm.(1.0 in.)

c. Finalization of Sheet Rolling Procedure

The finalization of warm rolling and finishing practices included a study of the effect of warm rolling and finishing variables on 0.025-0.102 cm.(0.010-0.040 in.) sheet quality, yield, elevated temperature tensile properties and room temperature ductility and/or formability. A detailed description of this work follows:

(1.) Rolling Temperature: Previous Fansteel/Du Pont work narrowed the warm rolling temperature range to 538-816° C (1000-1500° F). The purpose of the present work is to further narrow this range.

Intermediate gauge plate, 0.356 cm.(0.140 in.) thick, from Heat 3280 was rolled to 0.102 and 0.051 cm. (0.040 and 0.020 in.) utilizing furnace temperatures of 649°, 704°, 760° and 816° C(1200°, 1300°, 1400° and 1500° F). Rolling trials at 538° C(1000° F) were made with intermediate gauge plate from Heat 3285. Differences in edge cracking, number of passes through the mill to reach final gauge, and gauge

uniformity were measured. The effect of rolling temperature on the development of metallurgical structure and mechanical properties is discussed in a later part of this section of the report.

The amount of edge cracking in the temperature range of 649-816°C(1200-1500°F) was found to be relatively constant, Table 8. At 538°C(1000°F), however, edge cracking was severe, causing a loss of almost 50% of the sheet width.

The total number of passes and the percent reductions per pass to reach final gauge from the initial 0.356 cm.(0.140 in.) thickness were temperature dependent as shown in Table 9. Rolling at 649-704°C(1200-1300°F) required almost twice the number of passes as rolling at 816°C(1500°F).

Gauge uniformity, as shown in Table 10, was not temperature dependent. The thickness ranges measured on the as-rolled sheet indicate that the goal tolerances of ±0.0076 cm. (±0.003 in.) for 0.102 cm.(0.040 in.) gauge and ±0.0051 cm. (±0.002 in.) for 0.051 cm.(0.020 in.) gauge can be met.

(2.) Reheating and Soaking Times: Prior to the initiation of the rolling experiments the furnaces were probed to determine existing temperature gradients. As shown in Figure 28, both were within the ±28°C(±50°F) tolerance specified for this work. The measurements were obtained using Chromel-Alumel thermocouples with a potentiometer; they were verified by optical pyrometry.

Heating studies were conducted with the heaviest gauge TDNiCr sheet. The time necessary to heat the 0.32 cm. (1/8 in.) TDNiCr sheet and 0.57 cm.(1/16 in.) cover plate combination to 816°C(1500°F) was found to be 20 minutes. A 30 minute heat-up period has been selected as standard rolling procedure.

The temperature of the steel cover plates dropped as much as 427°C(800°F) as a result of two rolling passes and exposure at ambient temperature during transfer to and from the rolling mill. The time required for reheating 0.051 cm.(0.020 in.) TDNiCr sheet (between cover plates) to temperature after two rolling passes was found to be less than 8 minutes. In all gauge thicknesses, 10 minutes was sufficient to raise the temperature to nominal. The 10 minute reheat period is now part of standard rolling practice.

The effectiveness of using cover plates as thermal insulators is shown in Figure 29, where cover plate surface temperatures and TDNiCr sheet surface temperatures are plotted as a function of time after removal from the furnace. Transfer time from the furnace to the rolling mill is approximately 5-10 seconds.

(3.) Canning Procedures: Three can designs were being investigated for improvements in yield (edge cracking) and surface finish:

- End and edge borders of steel to prevent movement of TDNiCr sheet during rolling, Figure 30.

TABLE 8

EDGE CRACKING AS A FUNCTION OF ROLLING TEMPERATURE

Temp.	Heat	Initial Width cm.	Loss In Width Rolled 0.360→0.102 cm.	Loss In Width Rolled 0.360→0.102 cm.
538°C	3285	25.4 cm.	10.16 cm.*	-
649°C	3280	30.5 cm.	4.13 cm.	5.40 cm.
704°C	3280	30.5 cm.	2.54 cm.	4.44 cm.
760°C	3280	30.5 cm.	1.91 cm.	4.44 cm.
816°C	3280	30.5 cm.	3.81 cm.	5.40 cm.

*Rolling discontinued at 0.249 cm. due to severe edge cracking.

TABLE 8

EDGE CRACKING AS A FUNCTION OF ROLLING TEMPERATURE

Temp.	Heat	Initial Width in.	Loss in Width Rolled 0.140 →0.040 in.	Loss in Width Rolled 0.140 →0.020 in.
1000°F	3285	10 in.	4 in.*	-
1200°F	3280	12 in.	1-5/8 in.	2-1/8 in.
1300°F	3280	12 in.	1.0 in.	1-3/4 in.
1400°F	3280	12 in.	3/4 in.	1-3/4 in.
1500°F	3280	12 in.	1-1/2 in.	2-1/8 in.

*Rolling discontinued at 0.098in. due to severe edge cracking.

TABLE 9

ROLLING REDUCTION AS A FUNCTION OF TEMPERATURE

Rolling Temp. °C	Rolling Temp. °F	Heat	No. of Passes to 0.102 cm. (0.040 in.)	No. of Passes to 0.051 cm. (0.020 in.)	Average Reduction per Pass
538	1000	3285*	-	-	2%
649	1200	3280	19	33	6.2%
704	1300	3280	18	28	6.7%
760	1400	3280	13	20	9.9%
815	1500	3280	11	18	11.6%

*Rolling discontinued at 0.249 cm. (0.098 in.) due to severe edge cracking.

TABLE 10

GAUGE UNIFORMITY AS A FUNCTION OF ROLLING TEMPERATURE

HEAT 3280

Rolling Temp.		0.102 cm. (0.040 in.) Sheet Thickness Range*		0.051 cm. (0.020 in.) Sheet Thickness Range*	
°C	°F	cm.	in.	cm.	in.
649	1200	0.0081	0.0032	0.0074	0.0029
704	1300	0.0074	0.0029	0.0071	0.0028
760	1400	0.0056	0.0022	0.0079	0.0031
816	1500	0.0053	0.0021	0.0069	0.0027

*Thickness Range - difference between maximum and minimum values as measured by Vidigage.

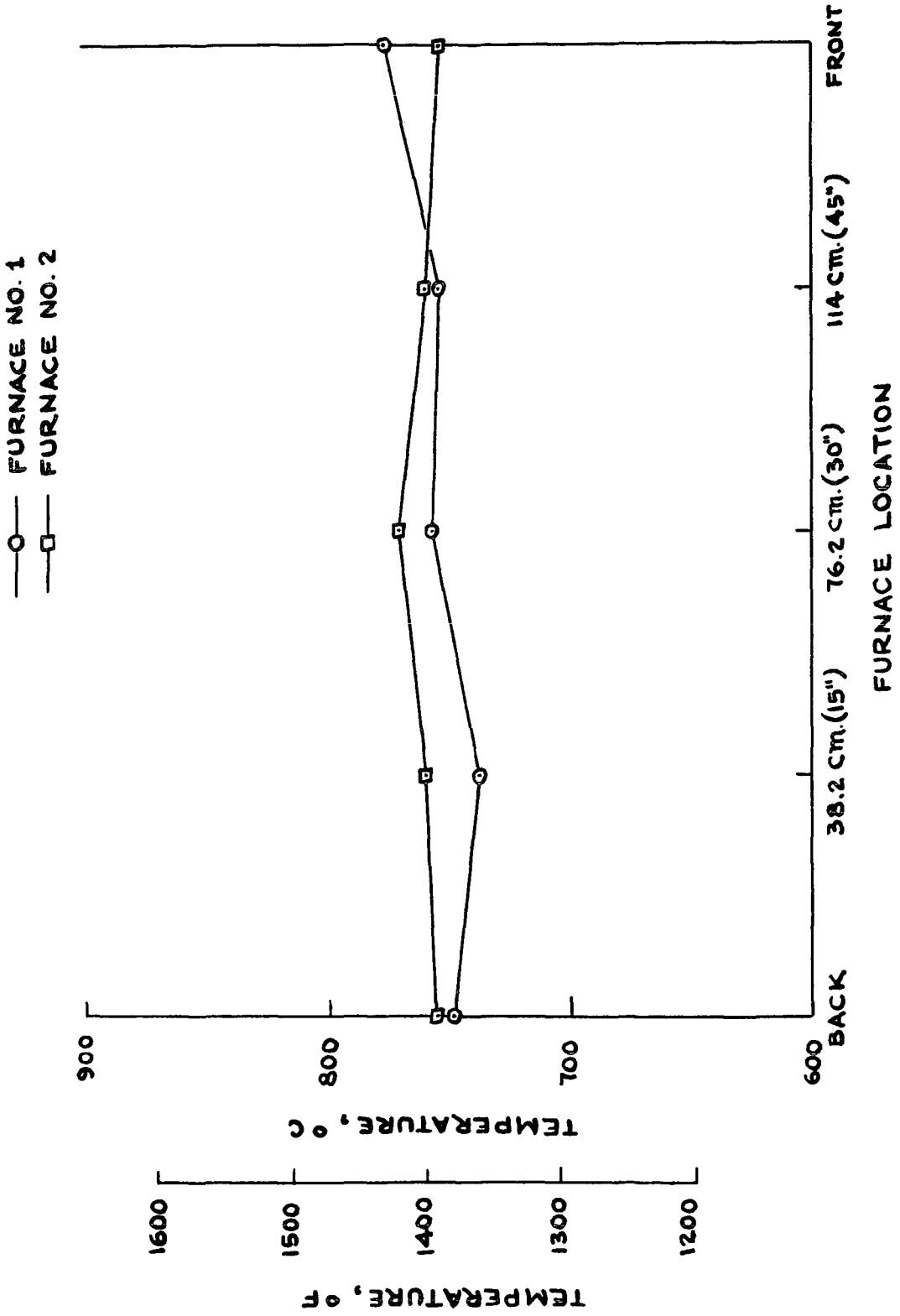


FIGURE 28 - FURNACE TEMPERATURE SURVEYS

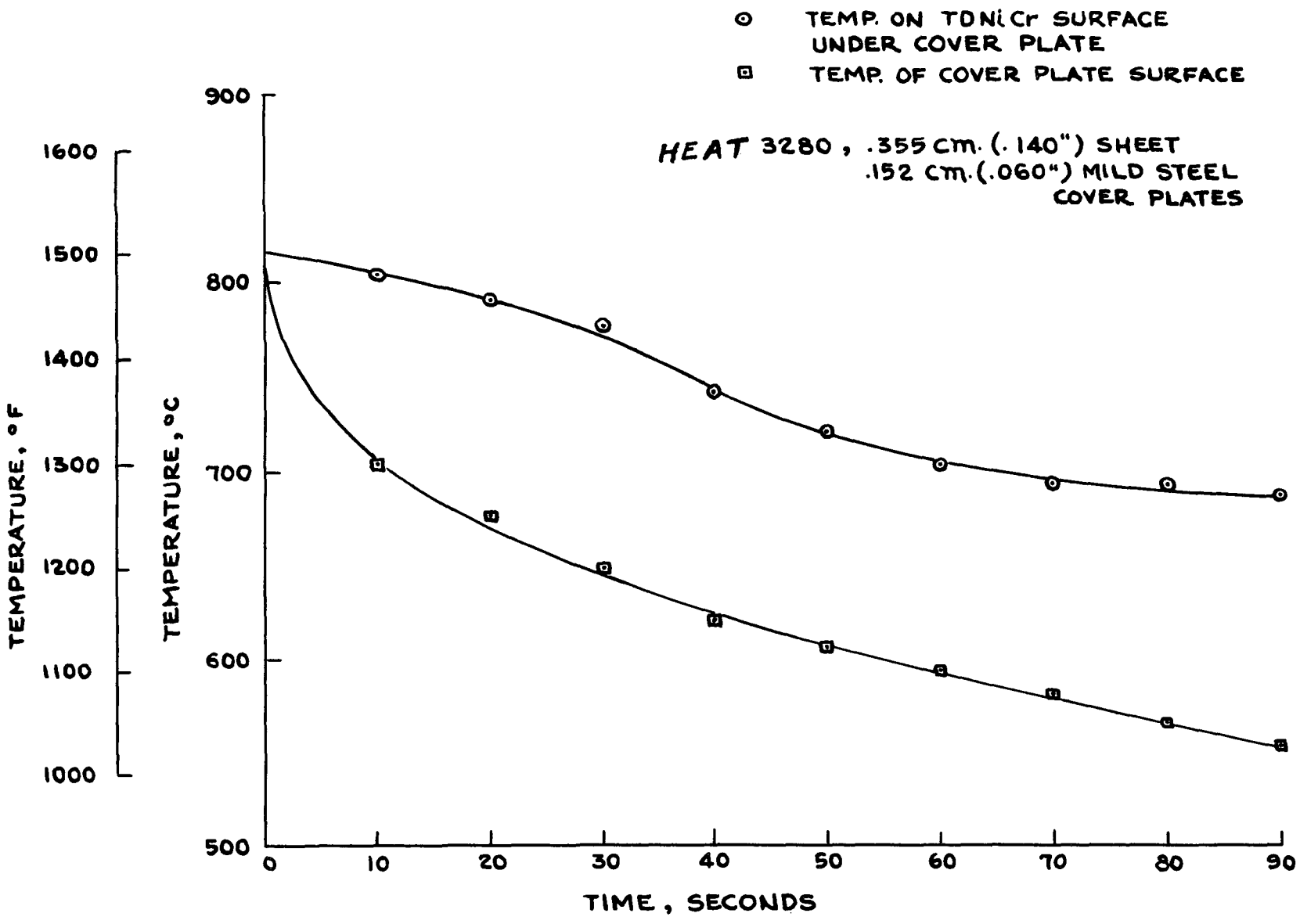


FIGURE 29 - COOLING CURVES FOR TDNiCr SHEET IN STEEL COVER PLATES

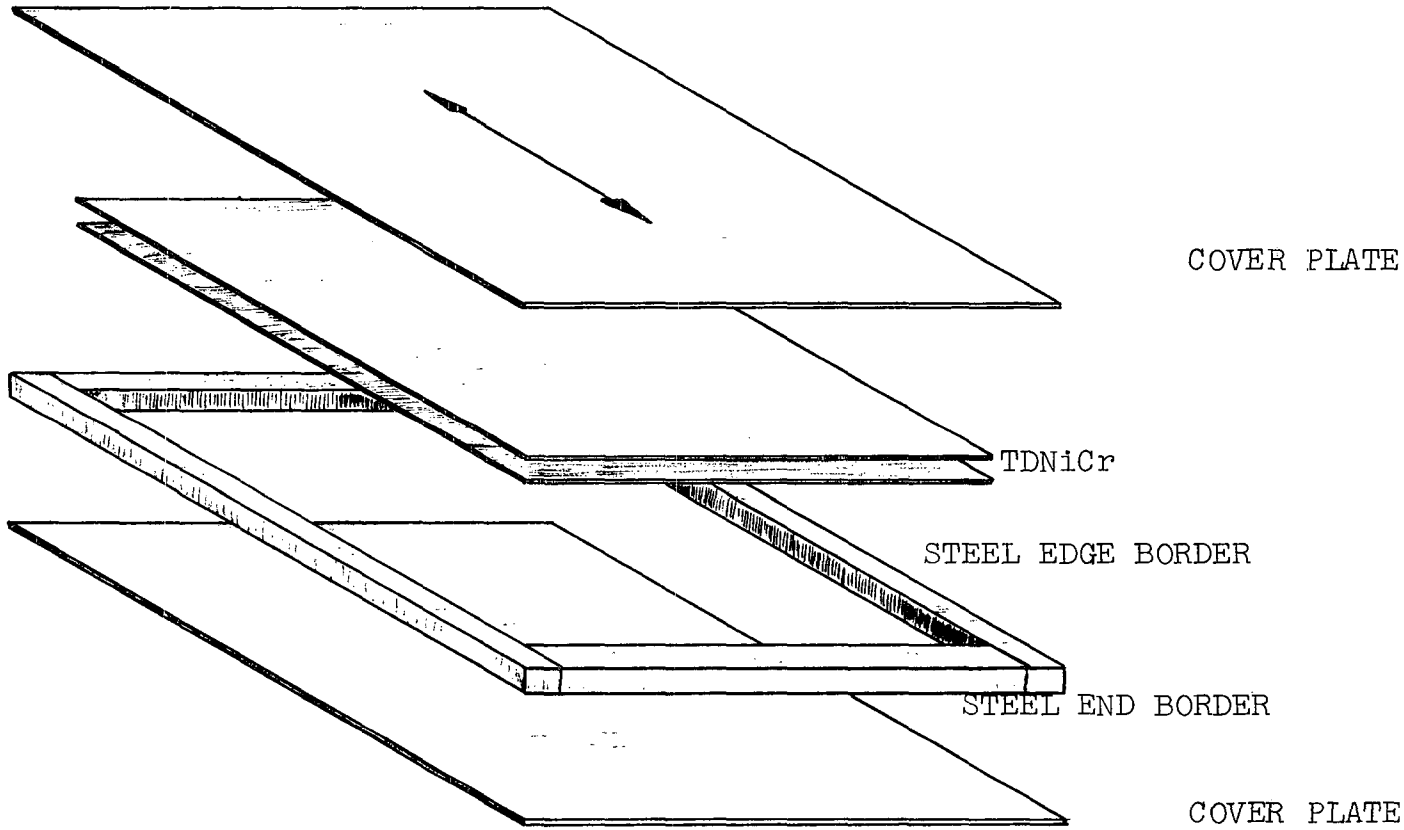


FIGURE 30

SPECIAL WARM ROLLING CAN CONFIGURATION

- Spot welded cover plates; on both end and edge. Previous practice has utilized spot welding only on the ends.
- Aluminized steel cover plates with spot welded ends. Surface improvement is expected to result from a reduction in the oxidation of the cover plates.

Edge cracking results on one heat, Table 11, indicate differences between the various new configurations and the mild steel can design presently used. The picture frame design and the use of aluminized steel both appear to offer potential.

Aluminized steel and mild steel cans with resistance spot welded ends were rolled from an air furance to simulate the environment of the warm rolling oven installed for sheet size scale-up. The air atmosphere caused greater oxidation of the mild steel, with an adverse effect on "as-rolled" finish. Profilometer measurements, Table 12, were used to compare the as-rolled surfaces. The surface finishes of the aluminized and mild steel rolled with a hydrogen atmosphere are also listed. These data indicate that aluminized steel will produce TDNiCr sheet surfaces of the same quality whether heated in hydrogen or air. Removal of the oxides by standard chemical cleaning procedures was found to be successful.

TABLE 11

EDGE CRACKING AS A FUNCTION OF CAN DESIGN

Can Design	Loss in Sheet Width Rolled 0.36 cm.→0.102 cm. (0.14 in.→0.040 in.)	Loss in Sheet Width Rolled 0.36 cm.→0.051 cm. (0.140→0.020 in.)
1.) Aluminized Steel	0.32 cm. (1/8 in.)	3.81 cm. (1-1/2 in.)
2.) Spot Welded Edges	1.58 cm. (1/8 in.)	2.54 cm. (1 in.)
3.) "Picture frame"	0.64 cm. (5/8 in.)	1.91 cm. (3/4 in.)
4.) Standard Steel Can	2.54 cm. (1/4 in.)	5.40 cm. (2-1/8 in.)

Heat 3285, Rolling Temperature-760°C (1400°F)
Starting width 30.48 cm. (12 in.)

TABLE 12

AS-ROLLED SURFACE FINISH AS A FUNCTION OF HEATING ATMOSPHERE

HEAT 3285

Can Design	Surface Condition	Heating Atmosphere	Avg. rms finish Trans.	Long.
Alum. Steel	"As-rolled"	Hydrogen	32	37
Mild Steel	" "	Hydrogen	27	31
Alum. Steel	" "	Air	35	50
Mild Steel	" "	Air	130	130
Alum. Steel	After Cleaning	Air	20	40
Mild Steel	" "	Air	75	80

Solutions used to accomplish the cleaning cycle were as follows:

• Water	3.79 l(1 gal.)
Sodium hydroxide	1.06 l(36 oz.)
Potassium permanganate	0.27 l(9 oz.)
Temperature	100°C(212°F)
Time	1 to 2 hrs.
• Water rinse and wipe	
• Water	3.79 l(1 gal.)
Hydrochloric acid	0.118-0.354 l (1/4-3/4 pt.)
Ferric Chloride	0.044 l(1-1/2 oz.)
Temperature	Room
Time	1 to 1-1/2 hrs.
• Cold water rinse	
• Warm water rinse	
Water	3.79 l(1 gal.)
Nitric acid	1.18 l(2-1/2 pt.)
Hydrofluoric acid	0.24 l(1/2 pt.)
Temperature	516°C max.(125°F)
Time	60 min. max.
• Water rinse and wipe	

Preliminary results obtained on Heat 3285 indicated that the picture frame configuration and a conventional can design (spot welded ends) of aluminized steel were most promising. The former produced a slight decrease in edge cracking and the latter a marked improvement in surface finish over a mild steel can when rolled from an air furnace.

A second experiment was made to determine if the smaller material loss of the picture frame was due to its design or normal variations of edge cracking, this experiment utilized the following can designs:

a.) a "picture frame" with aluminized steel cover plates and mild steel edge borders and,

b.) the conventional design but with aluminized steel.

Ten inch wide sheets of 0.32 cm.(0.125 in.) Heat 3283 were canned as above and rolled from the same furnace at 760°C(1400°F) with an air atmosphere. The results, shown below, indicate that edge cracking was equivalent for both.

Can Design	Loss of Sheet Width 0.32→0.102 cm. (0.125→0.040 in.)	Loss of Sheet Width 0.32→0.051 cm. (0.125→0.020 in.)
Aluminized Steel Picture Frame	1.27 cm.(1/2 in.)	2.54 cm.(1 in.)
Conventional Can, Aluminized Steel	1.27 cm.(1/2 in.)	2.54 cm.(1 in.)

Gauge uniformity was not affected by the can designs listed in Table 11; the gauge variations were similar to those listed in Table 10.

Further, no difference could be detected in mechanical properties of either 0.051 or 0.102 cm.(0.020 or 0.040 in.) sheet as a result of can material employed.

C.9

(4.) Recrystallization Heat Treatment: Samples obtained from sheet product rolled at furnace temperatures of 649°, 704°, 760° and 816°C (1200°, 1300°, 1400° and 1500°F) were each subjected to 2 hour laboratory recrystallization heat treatments at 871°, 927°, 982°, 1177° and 1232°C (1600°, 1700°, 1800°, 2150° and 2250°F). The samples recrystallized at 871°, 927° and 982°C (1600°, 1700° and 1800°F) were heated to 1177°C(2150°F) for 2 hours for microstructural stabilization prior to cooling to room temperature. A special cycle which simulates plant conditions was also included. This cycle utilizes a slow heat up, 704°C→1177°C @ 37.78°C/half-hour,(1300°F→2150°F @ 100°F/half-hour) followed by a 2 hour hold at 1177°C(2150°F). The samples were then examined for differences in microstructure such as grain size and percent recrystallization. Data from the experiments are listed in Table 13. A number of observations can be made from these data:

- The grain size behavior was approximately the same for 0.102 cm.(0.040 in.) and 0.051 cm. (0.020 in.) gauges for the same process conditions.
- Heat treatments at 927°, 982°, 1232°C (1700°, 1800°, 2250°F) gave equivalent grain sizes (average values of 0.075 mm, 0.066 mm and 0.061 mm respectively).

TABLE 13

RECRYSTALLIZATION AND GRAIN SIZE AS A FUNCTION OF HEAT TREATMENT PROCEDURE

Rolling Temp.	Heat	Gauge cm.	Gauge in.	GRAIN SIZE* 871°C (1600°F) mm	927°C (1700°F) mm	982°C (1800°F) mm	1177°C (2150°F) mm	1232°C (2250°F) mm	1177°C **(2150°F) Slow Heat-up mm
649°C (1200°F)	3280-1	0.051	0.020	0.052	0.066	0.057	0.098	0.070	0.100
		0.102	0.040	0.065	0.054	0.064	0.133	0.054	0.120
704°C (1300°F)	3280-2	0.051	0.020	0.060	0.071	0.067	0.140	0.062	0.128
		0.102	0.040	0.058***	0.084	0.052	0.100	0.070	0.208
760°C (1400°F)	3280-3	0.051	0.020	20% Rx	0.069	0.059	0.137	0.065	0.119
		0.102	0.040	20% Rx	0.086	0.082	0.132	0.060	0.130
816°C (1500°F)	3280-4	0.051	0.020	No Rx	0.090	0.078	0.160	0.043	0.140
		0.102	0.040	No Rx	0.081	0.076	0.123	0.064	0.113
			AVG.		0.075	0.066	0.127	0.061	0.132

* Grain size in mm measured by a line intercept technique on cross section micrographs. (See Appendix B)

** Represents Plant Furnace Conditions.

*** 90% Recrystallization

- Heat treatments at 1177° C(2150° F) for two hours and 1177° C(2150° F) via a programmed heat up gave equivalent grain sizes which were approximately twice as large as the other heat treatments.
- The 871° C(1600° F) heat treatment was too low to produce complete recrystallization for sheet rolled at the higher temperature.
- Grain sizes were not affected by the elevated temperature exposure at 1177° C(2150° F), i.e. no grain growth occurred.

Emphasis was placed on grain size because of its importance in determining elevated temperature strength. Mechanical properties were measured for the sheets rolled at 649° C and 760° C(1200° F and 1400° F) with heat treatments of 982° C/ 2 hrs. - 1177° C/2 hrs.(1800° F/2 hrs. - 2150° F/2 hrs.) and 1177° C(2150° F) via a programmed heat-up. Strength values appeared equivalent at both ambient and 1093° C(2000° F). The minimum bend radius, however, was influenced by the heat treatments, Table 14. These results correlate with the observed differences in grain sizes.

Based on these data, a 760° C(1400° F) rolling temperature was tentatively chosen for standing processing. The 816° C(1500° F) temperature could lead to recrystallization during rolling and, for temperatures below 760° C(1400° F), a much larger number of passes is required to reach the final gauges.

TABLE 14

BEND RADII FOR HEAT 3280 TDNiCr SHEET

Rolling Temp. °C	Rolling Temp. °F	Gauge cm.	Gauge in.	Heat Treat	Min. Bend Radius
760	1400	0.051	0.020	Slow heat to 1177°C (2150°F)	4T
760	1400	0.102	0.040	Slow heat to 1177°C (2150°F)	3T
649	1200	0.051	0.020	Slow heat to 1177°C (2150°F)	2.5T
649	1200	0.102	0.040	Slow heat to 1177°C (2150°F)	3.5T
760	1400	0.051	0.020	982°C/2 hrs. + 1177°C/2 hrs. (1800°F/2 hrs. + 2150°F/2 hrs.)	<1.5T
760	1400	0.102	0.040	982°C/2 hrs. + 1177°C/2 hrs. (1800°F/2 hrs. + 2150°F/2 hrs.)	2.5T
649	1200	0.051	0.020	982°C/2 hrs. + 1177°C/2 hrs. (1800°F/2 hrs. + 2150°F/2 hrs.)	1 T
649	1200	0.102	0.040	982°C/2 hrs. + 1177°C/2 hrs. (1800°F/2 hrs. + 2150°F/2 hrs.)	3 T

Pilot sheets, at intermediate gauge plate, from seven different lots of TDNiCr were rolled to 0.038/0.051 cm. (0.015/0.020 in.) gauge utilizing the following procedures:

- Can in conventional manner at intermediate gauge plate thickness.
- Roll a pilot sheet at both 649° and 760°C (1200° and 1400°F) furnace temperature to finish gauges of 0.038 and/or 0.051 cm. (0.015 and/or 0.020 in.) thickness.
- Chemical clean.
- (a) Recrystallize one piece of each heat at 1177°C(2150°F) for two hours via program heat-up in dry hydrogen.
  (b) Recrystallize one piece of each heat at 1177°C(2150°F) for two hours in dry hydrogen.
  (c) Recrystallize one piece of each heat at 982°C(1800°F) for two hours - increase furnace temperature to 1177°C(2150°F) and hold for two hours.

Samples of each heat rolled at both 649° and 760°C(1200° and 1400°F) furnace temperatures and all three of the above outlined recrystallization temperatures were subsequently subjected to bend tests. In addition, metallographic evaluation was carried out to determine relative grain sizes. Evaluation

of the bend data, Table 15, indicated no dependence upon either heat treatment practice or rolling temperature. Further, the bend properties were all in the range of 4-5T and were thus outside the specification requirement of 3T. The strength properties all were within the specification limits.

The behavior of the pilot sheets from the seven lots of TDNiCr thus differed from the behavior of the material from Heat 3280 which had originally been used to determine the effect of rolling temperature and recrystallization temperature. Examination of the metallographic samples indicated that after heat treatment the grain sizes of the seven pilot sheet materials were all larger than those previously observed regardless of the combination of rolling and recrystallization parameters chosen. These behaviors, bend and grain size, indicate a difference in the material at the intermediate gauge plate thickness. The difference was subsequently shown to be related to the ThO_2 size at the start of the intermediate temperature rolling schedule. Additional process studies were required to further define the process and in-process controls required for reproducibility.

(5.) Effect of Cr_2O_3 Content

Earlier studies carried out during the optimization runs utilized a 954°C and 1066°C(1750°F and 1950°F) sintering temperature to determine effect of Cr_2O_3 content and size as a result of sintering temperature. It was believed that less Cr_2O_3 might improve ductility as indicated by standard bend test evaluation. These studies did not indicate any reduction of

TABLE 15

BEND RADIUS AS A FUNCTION OF PROCESS

Heat No.	Gauge cm.	Gauge in.	Bend Radius: 982°C+1177°C Rx (1800°F+2150°F Rx)	Bend Radius: 1177°C (2150°F) 2 hr. Rx.	Bend Radius: 1177°C (2150°F) via Program Heat-Up
3437-1	0.051	0.020	4.7	4.7	4.3
3437-2	0.051	0.020	4.1	4.1	4.3
3438-1	0.051	0.020	4.6	5.4	4.7
3438-2	0.051	0.020	-	-	-
3439-1	0.051	0.020	4.7	4.5	4.7
3439-2	0.051	0.020	3.8	3.5	3.9
3440-1	0.051	0.020	4.3	4.3	4.3
3440-2	0.051	0.020	3.6	3.1	4.2
3441-1	0.051	0.020	4.3	3.9	4.5
3441-2	0.051	0.020	4.2	3.6	3.8
3454-1	0.038	0.015	4.6	4.6	4.6
3454-2	0.038	0.015	4.6	5.2	5.2
3468-1	0.038	0.015	3.6	3.7	4.3
3468-2	0.038	0.015	4.3	4.3	3.9
AVERAGE			4.3	4.2	4.4

* 1 - represents 649°C (1200°F) furnace temperature for rolling

2 - represents 760°C (1400°F) furnace temperature for rolling

Cr_2O_3 as a result of a higher sinter temperature of 1066° C (1950° F). It was also shown that no significant increase in thoria size was attained as a result of the 1066° C(1950° F) sintering temperature in comparison to the 954° C(1750° F) temperature. Therefore, it was concluded that the permissible upper limit on the sintering temperature had not been reached. For this reason Heat 3507, from the 50 - 45.36 kg.(100 lb.) units scheduled for production sheet, was sintered at 1177° C (2150° F) rather than either the 954° C or 1066° C(1750° F or 1950° F) temperatures previously employed. An insignificant increase in billet shrinkage was observed. This unit was subsequently canned by conventional techniques for roll consolidation and was roll consolidated at 1177° C(2150° F) furnace temperature rather than the usual 1010° C(1850° F) practice. Conventional rolling from the 2.54 cm.(1.0 in.) slab thickness to 0.102 and 0.051 cm.(0.040 and 0.020 in.) thickness sheet was carried out at 760° C(1400° F) at which point it was chemically cleaned and recrystallized at 1177° C(2150° F) via the program heat up and held for 2 hours in a dry hydrogen atmosphere. Mechanical properties at ambient and 1093° C(2000° F) temperatures are shown in Table 16.

The properties, Table 16, indicate that sheet product manufactured with the 1177° C(2150° F) sinter and roll consolidation temperatures met the specification requirements without any decrease in strength at either ambient or 1093° C (2000° F) temperatures. Metallographic examination revealed almost no difference in Cr_2O_3 content except at the surface of

the sheet. A thin surface layer showed almost no Cr_2O_3, however, the layer was essentially removed by the finishing processes.

Additional work is being carried out in an effort to increase the depth of Cr_2O_3 free material on billets sintered at the 1177°C(2150°F) temperature by varying temperature plateaus, holding times and effluent gas dew points.

(6.) Effect of ThO_2 Size

An additional evaluation was made on the TDNiCr Heat 3507, which was used for the Cr_2O_3 study. The ThO_2 size was measured at a number of steps in the process. The data are reported in Table 17.

The thoria size showed little change throughout the processing. The size attained as a result of the 1177°C (2150°F) sinter temperature and the 1177°C(2150°F) consolidation temperature was 18.1 mμ reported at the 2.54 cm.(1.0 in.) slab stage. The significance of the change to 21-22 mμ during rolling to 0.25 cm.(0.1 in.) plate is not known.

These results have been compared with ThO_2 size data from a number of heats processed previously during this program. Data from a number of billets prepared for the Consolidation Studies and also random billets prepared for fabrication of the 680.4 kgs.(1500 lbs.) of production sheet are presented in Table 18. Data are also presented in Table 18 for Heat 3280 used to study the rolling and heat treating parameters and for the seven heats which showed non-standard behavior when checked with pilot sheets.

It may be noted that the first ten heats in Table 18 all have thoria sizes in the unrecrystallized stage of processing of 14.5 mμ or greater, whereas the balance of the heats shown in the table have thoria sizes of 13.0 mμ or less. The latter group includes the seven heats which did not produce specification properties.

The mechanical properties for a number of the heats are presented in Table 19. The differences in ambient and 1093°C(2000°F) strength properties are small and all heats pass the Fansteel specifications for tensile and stress rupture properties. The bend test data, however, show marked differences which appear to be related to the unrecrystallized ThO_2 size. Materials having an unrecrystallized thoria size of 14.5 mμ or greater all pass the 3T specification bend requirement. Materials fabricated with an unrecrystallized thoria size of 13 mμ or less, all failed the 3T requirement. In addition, metallographic evaluation of finished sheet, subsequent to recrystallization, indicated that material containing unrecrystallized thoria size of 14.5 mμ or greater had an average grain diameter much smaller than the grains in material containing an unrecrystallized thoria size of 13 mμ or less. It appears, therefore, that ThO_2 size can be too small. It then is necessary to control the ThO_2 size during the processing to obtain the desired balance of properties.

ThO_2 size control can be exercised at three points in the manufacturing process. ThO_2 growth can be controlled in the powder manufacture, in the sintering practice and in the consolidated and hot rolled slab.

TABLE 16

MECHANICAL PROPERTIES OF 0.051-0.102 cm. SHEET FABRICATED FROM BILLET SINTERED AT 1177°C

Heat No.	Gauge cm.	ROOM TEMPERATURE UTS MN/m^2	YS MN/m^2	Elong. % cm.	1093°F UTS MN/m^2	YS MN/m^2	Elong. % cm.	3T Bend Trans.	Stress Rupture 20 hrs. at 1093°C 37.9 MN/m^2
3507	0.102	799.2	525.7	29.0	123.3	123.3	3.0	OK	OK
3507	0.051	835.0	556.7	23.0	126.8	126.8	4.0	OK	OK

TABLE 16

MECHANICAL PROPERTIES OF 0.020-0.040 SHEET FABRICATED FROM BILLET SINTERED AT 2150°F

Heat No.	Gauge in.	ROOM TEMPERATURE UTS ksi	YS ksi	Elong.% in inches	2000°F UTS ksi	YS ksi	Elong.% in inches	3T Bend Trans.	Stress Rupture 20 hrs. at 2000°F 5,500 psi Load
3507	0.040	116.0	76.3	29.0	17.9	17.9	3.0	OK	OK
3507	0.020	121.2	80.8	23.0	18.4	18.4	4.0	OK	OK

TABLE 17

THORIA SIZE AT VARIOUS PROCESSING STAGES FOR HEAT 3507

Processing Stage			Thoria Size
Cm.	In.		mμ
2.54	1	Slab - UnRx	18.1
0.254	0.1	Plate - UnRx	21.5
0.102	0.040	Sheet - UnRx	21.0
0.102	0.040	Sheet - 1177°C (2150°F) Rx	22.0
0.051	0.020	Sheet - UnRx	21.0
0.051	0.020	Sheet - 1177°C (2150°F) Rx	22.0

TABLE 18

THORIA SIZE DATA FOR A SERIES OF TDNiCr HEATS

	ThO_2 Size - mμ				
Heat	0.254 cm. (0.1 in.) Plate UnRx	0.102 cm. (0.040 in.) Sheet UnRx	0.102 cm. (0.040 in.) Sheet Rx	0.051 cm. (0.020 in.) Sheet UnRx	0.051 cm. (0.020 in.) Sheet Rx
3278*		16.5	22.0		
3279*		14.5	26.5		
3281*		14.5	28.5		
3283*		14.5	26.5		
3321*	15.0				20.0
3323*	15.0		23.5		
3280		18.5	22.0		
3282		19.0	23.5		
3284		19.0	21.0		
3285		15.5	20.0		
3362	13.0				19.0
3363	12.5				19.0
3386	12.0				18.5
3418	11.5		15.5		
3437	12.5			12.0	
3438				9.5	
3439				11.5	
3440	12.5			12.0	
3441	11.5			11.0	
3454				11.5	
3468				13.0	17.5

* Heats consolidated by forging; balance of heats consolidated by rolling.

The ThO_2 size in Heat 3440 was measured after consolidation and hot rolling at 1010°C(1850°F). The ThO_2 growth characteristics were measured at a series of temperatures and times and the data are reported in Table 20. Growth can thus be controlled at this process stage in the size range desired.

Samples from a series of seven heats, 3473, 3493, 3494, 3499, 3501, 3508 and 3510 in process of fabrication for the 680.4 kg.(1500 lb.) production sheet requirement were obtained at the 2.54 cm.(1.0 in.) slab stage of processing. All seven of these heats were compacted by standard practice, sintered at 954°C(1750°F), roll consolidated at 1010°C(1850°F) and decanned for conditioning at the 2.54 cm.(1.0 in.) slab size. Thoria sizes of the seven heats in the unrecrystallized stage at this size were found to be as indicated in Table 21. The samples were heat treated for two hours at 1177°C(2150°F) and thoria sizes again determined. The resultant sizes obtained are also shown in Table 21. The thoria size attained as a result of the 1177°C(2150°F) heat treatment was found to be comparable to that attained on Heat 3507 which had been sintered at 1177°C(2150°F), e.g. 18 to 21 mμ, as indicated in Table 17.

The seven heats listed in Table 21 were subjected to a 2 hour heat treatment at 1177°C(2150°F) in the conditioned 2.54 cm.(1.0 in.) slab condition. All seven heats were subsequently rolled to 0.25 cm.(0.100 in.) intermediate gauge plate and to

final gauges as shown in Table 22. Mechanical properties were then obtained on finish gauge sheets in addition to intermediate gauge samples in certain instances. The results of these tests are summarized in Table 22. Evaluation of these data indicate that bend test requirements were satisfied or exceeded at all gauges tested. The room temperature and elevated temperature tensile properties were also satisfactory at all gauges. However, the stress rupture results on Heats 3473 and 3493 at 0.102 cm. (0.040 in.) and 0.127 cm.(0.050 in.) respectively were marginal.

Metallographic evaluation of these heats indicated that a finer grained structure was obtained on the 0.102 cm. (0.040 in.) and 0.127 cm.(0.050 in.) gauges than on 0.051 cm. (0.020 in.) or 0.076 cm.(0.030 in.) gauges made from the same heats. These finer grained structures were believed to be the cause of the marginal stress rupture results.

Apparently the lower reduction required to roll sheet to 0.102-0.127 cm. (0.040-0.050 in.) thickness from the standard 2.54 cm.(1.0 in.) slab was not sufficient to assure the proper deformation texture with a ThO_2 size in the range of 20 mμ. A review of previous process experience of TDNiCr sheet by Fansteel, prior to the present NASA contract, indicated that the ThO_2 size of extruded and/or forged sheet bar prior to warm rolling to gauges from 0.102 to 0.178 cm. (0.040 to 0.070 in.) was generally in the 14-19 mμ range. A ThO_2 size in this range appears necessary at the 2.54 cm.(1.0 in.) slab stage to attain proper deformation texture of 0.102-0.127 cm.(0.040-0.050 in.)

TABLE 19

MECHANICAL PROPERTIES & THO_2 SIZE FOR A SERIES OF HEATS

Heat No.	UnRx ThO_2 Size	Rx Gauge Tested	Room Temperature UTS MN/m^2	Room Temperature YS MN/m^2	Room Temperature Elong. % cm	1093°C UTS MN/m^2	1093°C YS MN/m^2	1093°C Elong. % cm	1093°C 37.9 MN/m^2 >20 hrs.	Trans. Bend Test
3278	16.5	0.102	800.6	558.7	25.0	106.1	99.2	7.5	OK	2.5T
3279	14.5	0.102	822.7	562.9	27.1	106.1	103.3	6.0	OK	3.0T
3281	14.5	0.102	822.7	530.5	27.1	107.4	106.7	6.0	OK	3.0T
3283	14.5	0.102	833.0	545.7	27.0	112.3	111.6	6.0	OK	2.5T
3321	15.0	0.051	821.3	569.1	20.0	126.8	126.8	5.0	OK	3.0T
			869.5	629.0	18.5	115.0	115.0	5.0	OK	3.0T
3323	15.0	0.064	758.6	542.9	12.5	117.1	117.1	6.0	OK	3.0T
3280	18.5	0.102	847.5	575.3	25.0	115.0	113.6	4.5	OK	3.0T
3282	19.0	0.102	918.4	695.9	25.0	115.8	114.3	7.5	OK	3.0T
3284	19.0	0.102	831.6	544.3	25.0	108.2	106.1	7.5	OK	3.0T
3285	15.5	0.051	784.0	522.9	25.0	119.9	119.9	9.0	OK	<1.0T
3362	13.0	0.051	762.0	527.8	20.0	111.6	111.6	3.5	OK	5.0T
3363	12.5	0.051	784.8	549.8	25.5	131.6	128.2	6.0	OK	5.0T
3386	12.0	0.051	800.6	624.9	27.0	121.3	121.3	5.5	OK	6.0T
3418	11.5	0.102	864.0	701.4	14.5	115.8	115.8	3.5	OK	>4.0T
3468	13.0	0.051	784.8	515.3	24.0	138.5	137.1	5.0	OK	4.0T

TABLE 19

MECHANICAL PROPERTIES & ThO_2 SIZE FOR A SERIES OF HEATS

Heat No.	UnRx ThO_2 Size	Rx Gauge Tested	Room Temperature UTS ksi	Room Temperature YS ksi	Room Temperature Elong. %-in.	2000°F UTS ksi	2000°F YS ksi	2000°F Elong. %-in.	2000°F 5500 psi >20 hrs.	Trans. Bend Test
3278	16.5	0.040	116.2	81.1	25.0	15.4	14.4	7.5	OK	2.5T
3279	14.5	0.040	119.4	81.7	27.1	15.4	15.0	6.0	OK	3.0T
3281	14.5	0.040	119.4	77.0	27.1	15.6	15.5	6.0	OK	3.0T
3283	14.5	0.040	120.9	79.2	27.0	16.3	16.2	6.0	OK	2.5T
3321	15.0	0.020	119.2	82.6	20.0	18.4	18.4	5.0	OK	3.0T
			126.2	91.3	18.5	16.7	16.7	5.0	OK	3.0T
3323	15.0	0.025	110.1	78.8	12.5	17.0	17.0	6.0	OK	3.0T
3280	18.5	0.040	123.0	83.5	25.0	16.7	16.5	4.5	OK	3.0T
3282	19.0	0.040	133.3	101.0	25.0	16.8	16.6	7.5	OK	3.0T
3284	19.0	0.040	120.7	79.0	25.0	15.7	15.4	7.5	OK	3.0T
3285	15.5	0.020	113.8	75.9	25.0	17.4	17.4	9.0	OK	<1.0T
3362	13.0	0.020	110.6	76.6	20.0	16.2	16.2	3.5	OK	5.0T
3363	12.5	0.020	113.9	79.8	25.5	19.1	18.6	6.0	OK	5.0T
3386	12.0	0.020	116.2	90.7	27.0	17.6	17.6	5.5	OK	6.0T
3418	11.5	0.040	125.4	101.8	14.5	16.8	16.8	3.5	OK	>4.0T
3468	13.0	0.020	113.9	74.8	24.0	20.1	19.9	5.0	OK	4.0T

TABLE 20

THORIA SIZE IN HOT ROLLED SLAB
AS A FUNCTION OF HEAT TREATMENT

HEAT 3440

Sintered	954°C (1750°F)
Consolidated and Hot Rolled	1010°C (1850°F)
ThO_2 Size	12.0mμ

Temperature	ThO_2 Size - mμ			
	1 Hr.	2 Hrs.	4 Hrs.	5 Hrs.
954°C (1750°F)	13.5	12.5	13.5	
1010°C (1850°F)	13.5	14.5	13.5	
1066°C (1950°F)	16.5	15.5	16.5	
1121°C (2050°F)	16.5	17.5	18.5	20.0
1177°C (2150°F)	20.0	20.0	20.0	

TABLE 21

THORIA SIZE BEFORE AND AFTER

1177°C (2150°F) HEAT TREAT OF 2.54 cm.(1.0 in.) SLAB

TDNiCr

Heat No.	UnRx	Thoria Size After 1177°C (2150°F) for 2 hrs.
3473	12.0	20.0
3493	10.0	20.0
3494	12.5	21.0
3499	13.5	18.0
3501	12.0	20.0
3508	11.5	21.0
3510	13.0	20.0

TABLE 22

MECHANICAL PROPERTIES VS. FINISHED GAUGE SHEET

Heat No.	Gauge cm.	Room Temperature UTS MN/m^2	Room Temperature YS MN/m^2	Room Temperature Elong. % cm.	1093°C UTS MN/m^2	1093°C YS MN/m^2	1093°C Elong. % cm	1093°C Stress Rupture 37.9 MN/m^2 >20 hrs.	1093°C Stress Rupture 37.9 MN/m^2 <20 hrs.	Trans. Bend 3T	1093°C Stress Rupture 27.6 MN/m^2 >20 hr.
3473	0.025	865.4	640.0	20.0	114.4	114.4	5.0			OK	OK
3473	0.051	896.4	601.5	22.5	119.2	104.0	3.7	OK		OK	
3473*	0.102	872.9	579.4	21.5	125.4	123.3	3.5	3-tests OK	1 test	OK	
3493	0.051	834.4	553.8	22.0	121.9	121.9	3.0	OK		OK	
3493**	0.127	866.8	583.6	20.5	115.1	115.1	3.6	1-test OK	1 test	OK	
3494	0.051	817.8	544.9	25.0	114.4	102.7	2.8	OK		OK	
3499	0.051	915.7	531.9	22.5	124.0	124.0	4.5				
3501	0.076	802.7	523.6	18.0	139.2	137.1	3.0	OK		OK	
3508	0.076	824.0	520.9	22.5	143.3	141.9	5.0	OK		OK	
3510	0.051	830.9	571.2	22.5	126.1	124.7	3.0	OK		OK	

*Average of four tests.

**Average of two tests.

TABLE 22

MECHANICAL PROPERTIES VS. FINISHED GAUGE SHEET

Heat No.	Gauge in.	Room Temperature UTS ksi	Room Temperature YS ksi	Room Temperature Elong. %-in.	2000°F UTS ksi	2000°F YS ksi	2000°F Elong. %-in.	2000°F Stress Rupture 5500 psi >20 hrs.	2000°F Stress Rupture 5500 psi <20 hrs.	Trans. Bend 3T	2000°F Stress Rupture 4000 psi >20 hrs.
3473	0.010	126.5	92.9	20.0	16.6	16.6	5.0			OK	OK
3473	0.020	130.1	87.3	22.5	17.3	15.1	3.7	OK		OK	
3473*	0.040	126.7	84.1	21.5	18.2	17.9	3.5	3-tests OK	1 test	OK	
3493	0.020	121.1	80.5	22.0	17.7	17.7	3.0	OK		OK	
3493**	0.050	125.8	84.7	20.5	16.7	16.7	3.6	1-test OK	1-test	OK	
3494	0.020	118.7	79.1	25.0	16.6	14.9	2.8	OK		OK	
3499	0.020	132.9	77.2	22.5	18.0	18.0	4.5				
3501	0.030	116.5	76.0	18.0	20.2	19.9	3.0	OK		OK	
3508	0.030	119.6	75.6	22.5	20.8	20.6	5.0	OK		OK	
3510	0.020	120.6	82.9	22.5	18.3	18.1	3.0	OK		OK	

* Average of four tests.

** Average of two tests.

sheet and thus yield satisfactory microstructure and mechanical properties.

Further process heat treatment studies were made to evaluate their effect on ThO_2 size. The data reported in Table 20 for Heat 3440 indicated that a temperature of 1093°C (2000°F) for a period of one to two hours should yield a ThO_2 size of 16.5 mμ which is the mid point of the 14 to 19 mμ range mentioned previously. Samples from three additional heats at the 2.54 cm.(1.0 in.) slab stage of processing were also subjected to temperatures of 1093°C and 1177°C (2000°F and 2150°F) to evaluate ThO_2 growth characteristics. The results of these data are reported in Table 23. It may be noted that the ThO_2 size results obtained on these three heats subsequent to the 1093°C and 1177°C (2000°F and 2150°F) heat treatments were comparable to those shown in Table 20 for Heat 3440.

Based upon these results, a series of 45.4 kg. (100 lb.) TDNiCr units at the 2.54 cm.(1.0 in.) conditioned slab stage of processing having as-rolled ThO_2 sizes ranging between 10.5 and 14 mμ were subjected to a two hour heat treatment at 1093°C(2000°F) and subsequently rolled to the nominal 0.254 cm. (0.1 in.) intermediate gauge plate. At this stage of processing, ThO_2 sizes were again determined for the as-rolled plate and are also shown in Table 24. As these data indicate, the ThO_2 sizes obtained as a result of the two hour heat treat at 1093°C (2000°F) were on the high side of the anticipated size range. The average ThO_2 size subsequent to the 1093°C(2000°F) heat treat

TABLE 23

THORIA SIZE IN HOT ROLLED SLABS

AS A FUNCTION OF HEAT TREATMENT

Heat	ThO_2 Size - μ	
	2 hrs. @ 1093°C(2000°F)	2 hrs. @ 1177°C(2150°F)
3415	17.0	20.0
3456	17.0	21.0
3502	17.0	20.0

TABLE 24

EFFECT OF 1093°C (2000°F) HEAT TREATMENT FOR 2 HOURS ON TDNiCr ThO_2 SIZE

Heat	ThO_2 Size - μ	
	2.54 cm.(1.0 in.) Slab As-Rolled	Heat Treated-Rolled to 0.254 cm.(0.1 in.)
3626	13.5	18.0
3627	12.0	19.0
3628	12.0	17.5
3629	11.0	16.5
3630	14.0	20.0
3631	12.5	20.0
3632	12.5	17.5
3633	13.0	17.0
3634	12.5	18.5
3635	12.5	19.0
3636	10.5	20.0
3637	12.5	18.0
3638	12.0	18.0
3639	12.5	17.0
3640	12.5	17.5
3641	10.5	19.0

and 760°C(1400°F) deformation to 0.254 cm.(0.1 in.) intermediate plate was found to be 18.3 mμ. It may be noted that the spread of ThO_2 size data at the 0.254 cm.(0.1 in.) thickness was 3.5 mμ and that the spread of ThO_2 size data at the 2.54 cm.(1.0 in.) thickness was also 3.5 mμ.

A summary of Mechanical Properties versus Gauge and Grain size for these sixteen heats heat treated at 1093°C (2000°F) are shown in Table 25.

Evaluation of grain sizes versus gauge of these sixteen heats indicates that as gauge decreases, grain size increases. The grain sizes shown in Table 25 were attained by averaging longitudinal and transverse grain sizes for each gauge at each heat. During individual examination of each gauge, it was noted that the 0.025 cm.(0.010 in.) sheet from the five heats represented had an average grain size of 0.114 mm which ranged from 0.076 to 0.18 mm. The 0.051 cm.(0.020 in.) sheet had an average grain size of 0.073 mm ranging from 0.057 to 0.100 mm in diameter. The 0.076 cm.(0.030 in.) sheet was found to have an average grain size of 0.045 mm ranging from 0.034 to 0.057 mm in diameter. Finally the 0.102 cm.(0.040 in.) sheet had an average grain size of 0.042 mm ranging from 0.031 to 0.053 mm in diameter. Comparison of the average grain size of each gauge, it appears that the grain size of the 0.025 cm.(0.010 in.) sheet is slightly less than 1.6 times the average grain size of the 0.051 cm.(0.020 in.) sheet and this sheet has an average grain size of slightly less than 1.6 times the average grain size of the 0.076 cm.(0.030 in.)

TABLE 25

MECHANICAL PROPERTIES VS. GAUGE AND GRAIN SIZE

Heat No.	Gauge cm.	Room Temperature UTS MN/m^2	Room Temperature YS MN/m^2	Room Temperature Elong. % cm.	1093°C UTS MN/m^2	1093°C YS MN/m^2	1093°C Elong. % cm.	Stress Rupture 1093°C 31.0 MN/m^2	Stress Rupture 1093°C 37.9 MN/m^2	Average Grain Size mm
3627	0.025	842.6	544.9	20.0	130.2	130.2	2.0	>20 hrs.		0.0762
3632	0.025	763.4	591.9	19.6	118.5	118.5	3.0	>20 hrs.		0.1079
3634	0.025	811.0	671.1	18.0	139.2	139.2	4.0	>20 hrs.		0.0615
3635	0.025	817.2	553.3	20.8	130.9	130.9	1.2	>20 hrs.		0.1879
3637	0.025	866.1	587.0	20.5	140.6	140.6	2.0	>20 hrs.		0.1384
3633	0.038	726.2	513.9	14.5	145.4	145.4	4.5	>20 hrs.		0.0724
3636	0.038	828.2	582.9	19.0	141.2	141.2	2.0	>20 hrs.		--
3629	0.051	822.0	593.9	25.0	150.2	150.2	2.5		>20 hrs.	0.0685
3630	0.051	868.9	583.6	20.3	143.3	142.6	5.0		>20 hrs.	0.0570
3636	0.051	815.8	578.8	19.0	136.4	136.4	2.0		>20 hrs.	0.1003
3640	0.051	775.1	530.5	22.5	141.9	141.9	3.5		>20 hrs.	0.0660
3626	0.076	840.0	543.6	22.3	124.0	124.0	2.5		>20 hrs.	0.0571
3628	0.076	876.4	604.9	20.8	128.8	128.8	2.5		>20 hrs.	0.0345
3638	0.076	826.1	537.4	20.0	132.9	132.9	2.5		>20 hrs.	0.0518
3639	0.076	853.0	547.0	20.5	139.2	139.2	2.5		>20 hrs.	0.0370
3631	0.102	830.2	624.2	14.5	141.2	141.2	2.0		>20 hrs.	0.0533
3636	0.102	908.1	628.4	22.5	123.3	118.5	4.9		>20 hrs.	0.0311
3641	0.038	NOT TESTED								

TABLE 25

MECHANICAL PROPERTIES VS. GAUGE AND GRAIN SIZE

Heat No.	Gauge in.	Room Temperature UTS ksi	Room Temperature YS ksi	Room Temperature Elong. %- in.	2000°F UTS ksi	2000°F YS ksi	2000°F Elong. %- in	Stress Rupture 2000°F 4500 psi	Stress Rupture 2000°F 5500 psi	Average Grain Size mm
3627	0.010	122.3	79.1	20.0	18.9	18.9	2.0	>20 hrs.		0.0762
3632	0.010	110.8	85.9	19.6	17.2	17.2	3.0	>20 hrs.		0.1079
3634	0.010	117.7	97.4	18.0	20.2	20.2	4.0	>20 hrs.		0.0615
3635	0.010	118.6	80.3	20.8	19.0	19.0	1.2	>20 hrs.		0.1879
3637	0.010	125.7	85.2	20.5	20.4	20.4	2.0	>20 hrs.		0.1384
3633	0.015	105.4	74.6	14.5	21.1	21.1	4.5	>20 hrs.		0.0724
3636	0.015	120.2	83.6	19.0	20.5	20.5	2.0	>20 hrs.		--
3629	0.020	119.3	86.2	25.0	21.7	21.7	2.5		>20 hrs.	0.0685
3630	0.020	126.1	84.7	20.3	20.8	20.7	5.0		>20 hrs.	0.0570
3636	0.020	118.4	84.0	19.0	19.8	19.8	2.0		>20 hrs.	0.1003
3640	0.020	112.5	77.0	20.5	20.6	20.6	3.5		>20 hrs.	0.0660
3626	0.030	121.9	78.9	22.3	18.0	18.0	2.5		>20 hrs.	0.0571
3628	0.030	127.2	87.8	20.8	18.7	18.7	2.5		>20 hrs.	0.0345
3638	0.030	119.9	78.0	20.0	19.3	19.3	2.5		>20 hrs.	0.0518
3639	0.030	123.8	79.4	20.5	20.2	20.2	2.5		>20 hrs.	0.0370
3631	0.040	120.5	90.6	14.5	20.5	20.5	2.0		>20 hrs.	0.0533
3636	0.040	131.8	91.2	22.5	17.9	17.2	4.9		>20 hrs.	0.0311
3641	0.015	NOT TESTED								

sheet. However, the average grain size of the 0.102 cm.(0.040 in.) sheet which was 0.042 mm appeared to be insignificantly smaller than that of the 0.076 cm. (0.030 in.) sheet.

The 0.102 cm.(0.040 in.) sheet heat treated at 1177°C(2150°F) had marginal 1093°C(2000°F) stress rupture properties and smaller grain size, Table 26, than the grain size on sheet subjected to the 1093°C(2000°F) heat treat at the 2.54 cm.(1.0 in.) slab size. It was believed, therefore, that an average minimal grain size of 0.030 mm was required for TDNiCr sheet of 0.102 cm.(0.040 in.) or less in thickness to yield satisfactory elevated temperature stress rupture properties.

A comparison was made of the average grain sizes of the previously discussed heats with the results obtained from the Reproducibility Experiments, to be described later. These data, given in Table 27, indicate that the average grain sizes in sheet produced employing a 1177°C(2150°F) heat treatment at the 2.54 cm.(1.0 in.) slab size are nearly the same or smaller as a result of increased ThO_2 size during the 760°C(1400°F) deformation. One exception, however, must be noted --- the average grain size of the 0.076 cm.(0.030 in.) sheet from Heat 3456 was abnormally large for still unexplained reasons.

The summary of Mechanical Properties versus Gauge and Grain size for the sixteen TDNiCr heats heat treated at 1093°C(2000°F), Table 25, shows that, in all cases, the properties satisfied the requirements of Fansteel Specifications S-DMM-S-01-R-0, dated January 1, 1969 and S-TC-S-01-R-1, dated December, 1969.

TABLE 26

AVERAGE GRAIN SIZE OF 0.102 cm.(0.040 in.)
TDNiCr SHEET SUBJECTED TO 1093°C(2000°F)
AND 1177°C(2150°F) AT 2.54 cm.(1.0 in.) SLAB THICKNESS

Heat No.	Heat Treat Temp. °C	Heat Treat Temp. °F	Average Grain Size Diameter mm
3493-2	1177	2150	0.0175
3499-1	1177	2150	0.0155
3473-1	1177	2150	0.0253
3473-2	1177	2150	0.0255
3473-3	1177	2150	0.0245
3473-4	1177	2150	0.0285
3631	1093	2000	0.0533
3636	1093	2000	0.0311
3623	1093	2000	0.0406
3634	1093	2000	0.0520
3630	1093	2000	0.0298

TABLE 27

AVERAGE GRAIN SIZE VS. TEMPERATURE

GAUGE cm.	GAUGE in.	AVERAGE GRAIN SIZE AND RANGE IN MM 1093°C(2000°F) H.T.	(Reproducibility Run) 1177°C(2150°F) H.T.
0.025	0.010	0.1144 (0.0762-0.1879)	0.0865
0.051	0.020	0.0730 (0.0570-0.1003)	0.0623
0.076	0.030	0.0451 (0.0345-0.0571	0.0470*

*Does not include 0.076 cm.(0.030 inch) sheet from Heat 3456

However, since this material was heat treated at the 2.54 cm.(1.0 in.) slab size at 1093°C(2000°F) rather than at 1177°C(2150°F), in a manner similar to the material fabricated for the reproducibility series, it is necessary to establish a relationship to evaluate mechanical properties as a function of the 2.54 cm.(1.0 in.) slab stage heat treat temperature and/or resultant ThO_2 size. Previously, it had been pointed out that the 0.102 cm.(0.040 in.) sheet produced utilizing a 1177°C (2150°F) heat treat had marginal stress rupture properties at the 1093°C(2000°F) test temperature while the 0.102 cm.(0.040 in.) sheet produced utilizing a 1177°C(2150°F) heat treat had marginal stress rupture properties at the 1093°C(2000°F) test temperature while the 0.102 cm.(0.040 in.) sheet produced utilizing the 1093°C(2000°F) heat treat had satisfactory 1093°C(2000°F) stress rupture properties. One point of difference in the two types of 0.102 cm.(0.040 in.) sheet has already been indicated as finished product grain size. However, this apparent difference does not appear to correlate in a particular reproducible trend with mechanical properties. Even the stress rupture failures do not appear to vary consistently. It was therefore decided to evaluate mechanical properties by statistical techniques. Stress rupture results do not lend themselves very appropriately to this type of analysis, therefore 1093°C(2000°F) ultimate tensile strength results were selected as the criterion of evaluation. This particular property was felt to be representative of the elevated temperature performance behavior. The heats involved in this evaluation consisted entirely of 45.4 kg. (100 lb.) units having been subjected to both the 1093°C(2000°F)

and 1177°C(2150°F) heat treatments at the 2.54 cm.(1.0 in.) slab stage of processing. They are shown in Table 28 along with respective gauges and 2.54 cm.(1.0 in.) heat treat temperatures.

The 1093°C(2000°F) transverse ultimate tensile strength from each unit at each gauge was obtained. These data were arranged in a frequency table using class intervals of 6.89 MN/m^2(1.0 ksi). Probability plots of the strengths, logarithms of the strengths and the square roots of the strengths were then prepared. From these plots, the data appeared to be best defined by a normal distribution.

All of the strength data were grouped according to heat and gauge as follows:

(1) 0.051 cm.(0.020 in.) and 0.076 cm.(0.030 in.) sheet utilizing a 2.54 cm.(1.0 in.) heat treat of 1177°C(2150°F).

(2) 0.051 to 0.102 cm. (0.020 to 0.040 in.) sheet utilizing a 2.54 cm.(1.0 in.) heat treat of 1093°C(2000°F).

(3) 0.025 cm.(0.010 in.) and 0.038 cm.(0.015 in.) sheet utilizing a 2.54 cm.(1.0 in.) heat treat of 1177°C(2150°F).

(4) 0.025 cm.(0.010 in.) and 0.038 cm.(0.015 in.) sheet utilizing a 2.54 cm.(1.0 in.) heat treat of 1093°C(2000°F).

(5) 0.102 cm.(0.040 in.) sheet utilizing a 2.54 cm. (1.0 in.) heat treat of 1177°C(2150°F).

Subsequently, arithmetic means ($\bar{X}$) and standard deviations (s) were then calculated for each of the above five data groupings. Following this, tests of significance were carried out on the arithmetic means and standard deviations of various data

groupings by comparing calculated F and t values with F and t values obtained from standard statistical tables. A 95 percent level of significance was chosen for this exercise.

The formulae employed were as follows:

$$F = \frac{s_1^2}{s_x^2} \text{ or } \frac{s_x^2}{s_1^2} \qquad \text{(larger of two numbers is numerator)}$$

where:

s_1 equals the standard deviation of data grouping (1) and s_x equals the standard deviation of data grouping (2), (3), (4), or (5) as expressed.

The table value of F is a function of the sample sizes and the level of significance. In the event that the table value of F is found to be less than the calculated value of F, a significant difference exists between the standard deviations of data groupings employed at the chosen level of significance.

$$t = \frac{\bar{X}_1 - \bar{X}_x}{s\left(\frac{1}{n_1} + \frac{1}{n_x}\right)^{\frac{1}{2}}}$$

where:

$\bar{X}_1$ equals the arithmetic mean of data grouping (1).

$\bar{X}_x$ equals the arithmetic mean of data grouping (2), (3), (4) or (5) as expressed.

TABLE 28

MATERIAL EMPLOYED FOR MECHANICAL PROPERTY STATISTICAL EVALUATION

Heat No.	Gauge cm.	Gauge in.	2.54 cm.(1.0 in.) Heat Treatment
3415	0.076	0.030	1177°C(2150°F)
3415	0.051	0.020	1177°C(2150°F)
3415	0.025	0.010	1177°C(2150°F)
3456	0.076	0.030	1177°C(2150°F)
3456	0.051	0.020	1177°C(2150°F)
3456	0.025	0.010	1177°C(2150°F)
3473	0.102	0.040	1177°C(2150°F)
3473	0.025	0.010	1177°C(2150°F)
3493	0.102	0.040	1177°C(2150°F)
3493	0.051	0.020	1177°C(2150°F)
3494	0.051	0.020	1177°C(2150°F)
3499	0.051	0.020	1177°C(2150°F)
3501	0.076	0.030	1177°C(2150°F)
3502	0.076	0.030	1177°C(2150°F)
3502	0.051	0.020	1177°C(2150°F)
3502	0.025	0.010	1177°C(2150°F)
3508	0.076	0.030	1177°C(2150°F)
3509	0.102	0.040	1177°C(2150°F)
3510	0.051	0.020	1177°C(2150°F)
3511	0.038	0.015	1177°C(2150°F)
3512	0.076	0.030	1177°C(2150°F)
3513	0.076	0.030	1177°C(2150°F)
3514	0.038	0.015	1177°C(2150°F)
3515	0.102	0.040	1177°C(2150°F)
3516	0.051	0.020	1177°C(2150°F)
3517	0.051	0.020	1177°C(2150°F)
3518	0.051	0.020	1177°C(2150°F)

TABLE 28
(CONT'D)

MATERIAL EMPLOYED FOR MECHANICAL PROPERTY
STATISTICAL EVALUATION

Heat No.	Gauge cm.	Gauge in.	2.54 cm. (1.0 in.) Heat Treatment
3626	0.076	0.030	1093°C(2000°F)
3627	0.025	0.010	1093°C(2000°F)
3628	0.076	0.030	1093°C(2000°F)
3629	0.051	0.020	1093°C(2000°F)
3630	0.051	0.020	1093°C(2000°F)
3630	0.038	0.015	1093°C(2000°F)
3632	0.025	0.010	1093°C(2000°F)
3634	0.025	0.010	1093°C(2000°F)
3635	0.025	0.010	1093°C(2000°F)
3636	0.051	0.020	1093°C(2000°F)
3636	0.038	0.015	1093°C(2000°F)
3637	0.025	0.010	1093°C(2000°F)
3638	0.076	0.030	1093°C(2000°F)
3639	0.076	0.030	1093°C(2000°F)
3640	0.051	0.020	1093°C(2000°F)
3640	0.038	0.015	1093°C(2000°F)
3631	0.102	0.040	1093°C(2000°F)

n_1, equals the sample size of data grouping (1).

n_x, equals the sample size of data grouping (2), (3), (4) or (5) as expressed.

s, equals the estimated standard deviation of the two data groupings in common and is defined by the following formula:

$$s^2 = \frac{(n_1-1)s_1^2 + (n_x-1)s_x^2}{n_1 + n_x - 2}$$

A value of t was obtained from standard statistical tables at the 95 percent level of significance for the appropriate sample sizes. In the event that the table value of t is less than the calculated value of t, a significant difference exists between the arithmetic means at a 95 percent level of significance.

Calculations for the various comparisons of data groupings are shown below:

- data grouping (1) - data grouping (2)

  (1) 0.051 cm.(0.020 in.) and 0.076 cm.(0.030 in.) 1177°C(2150°F)

  (2) 0.051 to 0.102 cm. (0.020 to 0.040 in.) 1093°C(2000°F)

  $\bar{X}_1$ = 130.5 MN/m^2 (18.91 ksi)

  n_1 = 83

  s_1 = 9.09 MN/m^2 (1.32 ksi)

$\bar{X}_2 = 135.4$ MN/m^2 (19.67 ksi)

$n_2 = 9$

$s_2 = 7.50$ MN/m^2(1.09 ksi)

$$F = \frac{s_1^2}{s_2^2} = \frac{82.5}{56.2} = 1.47 \text{ calculated}$$

F (Table at 95% level) = 2.99

Therefore, there is no significant difference between the standard deviations of data grouping (1) and (2).

$s^2 = 80.9$ TN^2/m^4 (1.69 ksi)

$s = 9.03$ MN/m^4 (1.31 ksi)

$$\text{then } t = \frac{\bar{X}_1 - \bar{X}_2}{5(1/n_1+1/n_2)^{\frac{1}{2}}} = 1.66 \text{ calculated}$$

t (table at 95% level) = 1.99

Therefore, there is no significant difference between the arithmetic means of data grouping (1) and (2).

- data grouping (3) - data grouping (4)

  (3) 0.025 cm.(0.010 in.) and 0.038 cm.(0.015 in.) 1177°C(2150°F)

  (4) 0.025 cm.(0.010 in.) and 0.038 cm.(0.015 in.) 1093°C(2000°F)

  $\bar{X}_3 = 125.9$ MN/m^2 (18.00 ksi)

  $n_3 = 38$

  $s_3 = 13.3$ MN/m^2 (1.93 ksi)

  $\bar{X}_4 = 132.8$ MN/m^2 (19.25 ksi)

  $n_4 = 10$

  $s_4 = 7.85$ MN/m^2 (1.14 ksi)

$$F = \frac{s_3^2}{s_4^2} = 2.89 \text{ calculated}$$

F (Table at 95% level) = 3.06

Therefore there is no significant difference between the standard deviations of data groupings (3) and (4).

s = 12.4 MN/m^2 (1.8 ksi)

t (calculated) = 1.95

t (Table at 95% level) = 2.02

Therefore, there is no significant difference between the arithmetic means of data grouping (3) and (4).

- data grouping (5) - data grouping (1)

(5) 0.102 cm.(0.040 in.) - 1177°C(2150°F)

and

(1) 0.051 cm.(0.020 in.) and 0.076 cm.(0.030 in.) 1177°C(2150°F)

$\bar{X}_5$ = 124.5 MN/m^2 (18.09 ksi)

n_5 = 15

s_5 = 8.61 MN/m^2 (1.25 ksi)

$\bar{X}_1$ = 130.5 MN/m^2 (18.91 ksi)

n_1 = 83

s_1 = 9.09 MN/m^2 (1.32 ksi)

$$F = \frac{s_1^2}{s_5^2} = 1.11 \text{ calculated}$$

F (Table at 95% level) = 2.20

Therefore, there is no significant difference between the standard deviations of data grouping (5) and (1).

t (calculated) = 2.23

t (Table at 95% level) = 1.98

Therefore, there is a significant difference between the arithmetic means of data grouping (5) and (1).

- data grouping (5) - data grouping (2)

(5) 0.102 cm.(0.040 in.) - 1177°C(2150°F)

and

(2) 0.051 to 0.102 cm. (0.020 to 0.040 in.) 1093°C(2150°F)

$\bar{X}_5$ = 124.5 MN/m^2 (18.09 ksi)

n_5 = 15

s_5 = 8.61 MN/m^2 (1.25 ksi)

$\bar{X}_2$ = 135.4 MN/m^2 (19.67 ksi)

n_2 = 9

s_2 = 7.50 MN/m^2 (1.09 ksi)

F (calculated) = 1.31

F (Table at 95% level) = 3.23

Therefore, there is no significant difference between the standard deviations of data grouping (5) and (2).

s = 8.25 MN/m^2 (1.20 ksi)

t (calculated) = 3.1

t (Table at 95% level) = 2.07

Therefore, there is a significant difference between the arithmetic means of data grouping (5) and (2).

Summarizing, no significant difference was found between either standard deviations or arithmetic means of elevated temperature tensile strengths of data grouping (1), 0.051 cm. (0.020 in.) and 0.076 cm.(0.030 in.) sheet heat treated at 2.54 cm. (1.0 in.) at 1177°C(2150°F) and data grouping (2), 0.051 to 0.102 cm.(0.020 to 0.040 in.) sheet heat treated at 2.54 cm. (1.0 in.) at 1093°C(2000°F). The same results were obtained when comparing data grouping (3), 0.025 cm.(0.010 in.) and 0.038 cm. (0.015 in.) sheet heat treated at 2.54 cm.(1.0 in.) at 1177°C (2150°F) and data grouping (4), 0.025 cm.(0.010 in.) and 0.038 cm. (0.015 in.) sheet heat treated at 2.54 cm.(1.0 in.) at 1093°C (2000°F). Therefore, it was concluded that use of the 1093°C (2000°F) heat treatment was comparable to the 1177°C(2150°F) heat treatment for 0.025 through 0.076 cm.(0.010 - 0.030 in.) TDNiCr sheet material. Further, the 1093°C(2000°F) heat treatment appeared satisfactory for 0.102 cm.(0.040 in.) material also, while the 0.102 cm.(0.040 in.) material processed with the 1177°C (2150°F) was found to have elevated temperature ultimate tensile strength arithmetic means having a significant difference from those of either 0.051 cm.(0.020 in.) and 0.076 cm.(0.030 in.) sheet heat treated at 1177°C(2150°F) or 0.051 to 0.102 cm.(0.020 to 0.040 in.) sheet heat treated at 1093°C(2000°F).

In conclusion a heat treat temperature of 1093°C (2000°F) is required at the 2.54 cm.(1.0 in.) slab stage of processing for ThO_2 size control to attain proper finished product grain size and satisfactory mechanical properties in TDNiCr sheet at gauges of 0.025 through 0.102 cm.(0.010 - 0.040 in.).

Based upon the results of these studies, ThO_2 size control will be utilized in the manufacture of sheet. ThO_2 measurements will be made for the powder and after consolidation of the slabs. An in-process heat treatment will be used as required to establish the desired ThO_2 size prior to rolling to gauge.

(7.) Process for 0.025-0.048 cm.(0.010-0.019 in.) Sheet

Finalization of the sheet rolling parameters for 0.025-0.048 cm.(0.010-0.019 in.) sheet was combined with the rolling study in the previous section.

Additionally, optimization of pack rolling procedures were investigated with particular emphasis on recanning-trimming steps required to reduce frequency of rolled-in particles of TDNiCr and/or steel can fragments.

Material for this portion of the evaluation was not available from that utilized for the reproducibility evaluation as stipulated in Exhibit A of the contract. Excess material from heats utilized for process development of 0.051 - 0.102 cm. (0.020 - 0.040 in.) sheet and material being processed to satisfy the TDNiCr sheet production requirements of Exhibit A were employed.

However, the optimized process developed during this evaluation was applied to portions of the three reproducibility heats for final reproducibility evaluation of 0.025 cm.(0.010 in.) sheet as stipulated in Exhibit A of the contract. Results of this work are included in the following section of this report.

The finalized isothermal rolling techniques for producing 0.025-0.048 cm.(0.010-0.019 in.) sheet were established using the same evaluation criteria as that employed on the 0.051-0.102 cm.(0.020-0.040 in.) sheet.

The primary process evolved from this work consists of warm pack rolling unrecrystallized sheet produced for 0.051-0.102 cm. (0.020-0.040 in.) sheet. The optimum number of sheets in a pack is four. It was determined that increasing the number to greater than four results in an increased probability of sheet movement within the can during rolling. Fewer sheets than four necessitated a "negative" roll gap setting (a zero setting with a roll separating force) on the mill currently in use. This practice was found to be detrimental to the shape of the finished sheet. Finally, the best shape and gauge control was found to be produced by decanning and recanning 0.0051 to 0.0076 cm. (0.002-0.003 in.) above the final gauge desired.

A segment of Heat 3280 was pack rolled to 0.025 cm. (0.010 in.) sheet at 760°C(1400°F) by this technique. Mechanical property tests of this material yielded the following results:

Room Temp.	UTS	799.2 MN/m^2 (116.0 ksi)
	YS	539.5 MN/m^2 (78.3 ksi)
	Elong.%	20.0
1093°C(2000°F)	UTS	127.5 MN/m^2 (18.5 ksi)
	Elong.%	2.0
1093°C(2000°F)	Stress Rupture	
	@ 31.0 MN/m^2(4500 psi)	>65 hrs.

As indicated by these data, this material satisfied the requirements of Fansteel Specifications S-TC-S-01-R-1 dated December 1, 1969 and S-DMM-S-01-R-0 dated January 1, 1969.

Additional finishing procedures were investigated for 0.025-0.048 cm.(0.010-0.019 in.) sheet. Previous work indicated that wide belt sanding of material less than 0.038 cm. (0.015 in.) thick was not practical because of grit pick up on sheet surfaces. As a result, work on an alternate finishing procedure was initiated with particular emphasis on 0.025 cm. (0.010 in.) sheet. The primary aim of the procedure was to develop a pickled-rolled finish for thin sheet. By this means, a sheet could be isothermally rolled to final gauge within required tolerance limits rather than rolling overgauge to allow removal of material by wide belt sanding. Accordingly, a yield improvement of approximately five to ten percent may be realized due to elimination of wide belt sanding and resultant material loss.

In order to accomplish this objective, the following fabrication procedure, identified as the pickle-rolled finish, was employed during the fabrication of twelve sheets of 0.025 cm. (0.010 in.) sheet from Heats 3322 and 3324.

- Warm pack roll to gauge
- Decan and shear trim edges and ends
- Immerse in solution of

Water	3.79 l. (1 gal.)
Sodium Hydroxide	1.06 l. (36 oz.)
Potassium Permanganate	.27 l. (9 oz.)

- Water rinse
- Wipe

- Immerse in solution of

Water	3.79 l.(1 gal.)
Hydrochloric Acid	.118-.354 l.(1/4-3/4 pt.)
Ferric Chloride	.044 l.(1-1/2 oz.)

- Water rinse
- Local condition as required
- Cold roll 2 to 5% reduction
- Recrystallize heat treat in dry H_2 for two hours at 1177°C(2150°F)

During the same processing campaign, four sheets of 0.025 cm.(0.010 in.) material were also processed by standard practices and were wide belt sanded.

A comparison of mechanical properties and microstructures revealed no differences which might be attributed to processing procedures.

During cold finish processing of these sheets, it was observed that very little reduction could be achieved on the single cluster configuration of the Schloemann Rolling Mill either by tension rolling or hand rolling, thus preventing the improved surface anticipated by this technique. Higher reductions could not be obtained because of the low ductility of the material in the unrecrystallized condition. Greater deformations can be attained by subjecting the sheets to a slight amount of cold work (up to 5% reduction) subsequent to a recrystallization heat treatment followed by a second heat treatment at 1177°C(2150°F) for 2 hours to insure a full stress relief and consequent stabilization of this material for eventual use in this temperature range.

This procedure, identified as the cold rolled-annealed finish consisted of the following steps:

- Warm pack roll to gauge
- Decan and shear trim edges and ends
- Immerse in solution of

Water	3.79 l.(1 gal.)
Sodium Hydroxide	1.06 l.(36 oz.)
Potassium Permanganate	.27 l.(9 oz.)

- Water rinse
- Wipe
- Immerse in solution of

Water	3.79 l.(1 gal.)
Hydrochloric Acid	.12-.35 l.(1/4-3/4 pt.)
Ferric Chloride	.044 l.(1-1/2 oz.)

- Water rinse
- Recrystallize heat treat in dry H_2 for two hours at 1177°C(2150°F)
- Local condition as required (i.e., abrasive belt polish)
- Hand wipe degrease
- Cold tension roll a maximum of 5% reduction
- Hand wipe degrease
- Recrystallize heat treat in dry H_2 for two hours at 1177°C(2150°F)
- Final shear, sample, inspect, test and ship

This processing practice was first evaluated on material from Heats 3414, 3419, 3435 and 3436. The properties obtained on this material are summarized in Table 29. Bend test results represent one sample per sheet. As indicated by these data, all the material satisfied the requirements of Fansteel Specifications S-TC-S-01-R-1 dated December 1, 1969 and S-DMM-S-01-R-0 dated January 1, 1969. In addition, the surface appearance and condition was improved over the pickle-rolled Scotch Brite finish initially evaluated.

As a result, the finishing procedure for processing 0.025-0.048 cm.(0.010-0.019 in.) sheet consists of utilizing the cold rolled-annealed technique on sheet less than 0.038 cm. (0.015 in.) in thickness and wide belt abrasive grinding of sheet 0.038 cm.(0.015 in.) or greater in thickness.

Future work shall evaluate the feasibility of utilization of the cold rolled-annealed finishing technique on 0.038 cm. (0.015 in.) or thicker sheet.

It should also be noted that while hand rolling is satisfactory for small sheets, the increased sheet size capability study requires the utilization of tension rolling in order to maintain satisfactory sheet shape.

(8.) Process Finalization

As a result of the work carried out and described in this report, a finalized process was established for the fabrication of 0.025 to 0.102 cm.(0.010 to 0.040 in.) TDNiCr sheet.

The process evolved is as follows:

(a.) Powder Manufacture

- Ni-20Cr-2ThO_2 - Nominal Composition
- ThO_2 size determination

(b.) Hydrostatic Compaction

- Rubber boot - No Mylar liner - Metal mesh container - 414 MN/m^2 (60,000 psi)
- 45.4 kg (100 lb) Unit 8.25 x 21.59 x 46.99 cm. (3-1/4 x 8-1/2 x 18-1/2 in.)-Nominal

(c.) Sinter

- 954°C(1750°F) in dry H_2 - Compact in mild steel can
- Dew point controlled to -57°C(-70°F) or better

(d.) Consolidate

- Roll to 2.54 cm.(1.0 in.) thickness
- Aluminized steel slip sheets
- Preheat canned unit to 1010°C(1850°F) in H_2 at dew point of -57°C(-70°F) or better, minimum of two hours - maximum of three hours.

(e.) Decan and Condition

- Saw crop edges and ends as required
- Mill, shape and/or grind surfaces as required
- Sample - ThO_2 size check

  (<15μ-Heat treat 2.54 cm.(1.0 in.) slab @ 1093°C(2000°F) for 2 hours)

  (>15μ, inclusive - No heat treat required)

TABLE 29

MECHANICAL PROPERTIES OF COLD ROLLED-ANNEALED 0.025 cm. SHEET

Heat No.	Gauge cm.	Room Temperature UTS MN/m^2	Room Temperature YS MN/m^2	Room Temperature Elong. % cm.	1093°C UTS MN/m^2	1093°C YS MN/m^2	1093°C Elong. % cm.	3T Bend T	3T Bend L	Stress Rupture 20 hrs. @ 1093°C 27.56 MN/m^2 Load
3414	0.025	749.6	536.7	21.9	95.8	95.8	2.5	OK	OK	OK
3419	0.025	701.4	505.0	20.9	93.0	89.6	3.0	OK	OK	OK
3435	0.025	704.2	514.7	17.5	104.0	104.0	4.0	OK	OK	OK
3436	0.025	835.8	620.1	20.0	75.1	75.1	4.0	OK	OK	OK
3436	0.025	766.9	551.2	19.5	-	-	-	OK	OK	-
3436	0.025	782.0	568.4	21.0	-	-	-	OK	OK	-
3436	0.025	796.5	584.3	20.0	-	-	-	OK	OK	-
3436	0.025	768.9	575.3	19.0	-	-	-	OK	OK	-

TABLE 29

MECHANICAL PROPERTIES OF COLD ROLLED-ANNEALED 0.010 in. SHEET

Heat No.	Gauge in.	ROOM TEMPERATURE UTS ksi	YS ksi	Elong.% in inches	2000°F UTS ksi	YS ksi	Elong.% in inches	3T Bend T	L	Stress Rupture 20 hrs. @ 2000°F 4000 psi Load
3414	0.010	108.8	77.9	21.9	13.9	13.9	2.5	OK	OK	OK
3419	0.010	101.8	73.3	20.9	13.5	13.0	3.0	OK	OK	OK
3435	0.010	102.2	74.7	17.5	15.1	15.1	4.0	OK	OK	OK
3436	0.010	121.3	90.0	20.0	10.9	10.9	4.0	OK	OK	OK
3436	0.010	111.3	80.0	19.5	-	-	-	OK	OK	-
3436	0.010	113.5	82.5	21.0	-	-	-	OK	OK	-
3436	0.010	115.6	84.8	20.0	-	-	-	OK	OK	-
3436	0.010	111.6	83.5	19.0	-	-	-	OK	OK	-

(f.) Recan

- Mild Steel

(g.) Roll to Intermediate Plate

- Preheat to 760°C(1400°F)
- Roll from 2.54 to 0.254 cm. (1.0 to 0.1 in.) (Recrystallize sample at 1177°C(2150°F) for two hours)

(h.) Decan, grind condition, chemical clean

(i.) Rolling to Gauge

- Recan in either 0.160 cm.(0.063 in.) or 0.180 cm.(0.071 in.) Armco Aluminized steel Type 1 or equivalent
- Preheat units to warm rolling temperatures of 760°C +0° -54°C (1400°F +0° - 100°F)
- Isothermally roll to gauge

(j.) Condition

- Chemical clean
- Grind and/or belt sand condition

(k.) Heat Treatment

- Recrystallize heat treatment - Program heat up to 1177°C(2150°F)/2 hours.
- Dry hydrogen atmosphere

(l.) Finishing - Gauges of 0.038 cm.(0.015 in.) and greater

- Roll level if required
- Wide belt abrasive grind to 32 rms or better

(m.) Finishing - Gauges of 0.025 cm.(0.010 in.) but less than 0.038 cm.(0.015 in.)

- Wide belt abrasive polish to 32 rms or better
- In process inspection for gauge and finish
- Shear

  Shear to square edges and/or ends
- Degrease
- Cold Roll

  Tension roll a maximum of 5% reduction
- Degrease
- Heat Treatment

  Program heat up to 1177°C(2150°F) for 2 hours

  Dry hydrogen atmosphere

(n.) Shear to Size

- In process inspection for gauge and finish
- Shear to finish size
- Sample

(o.) Inspection

- Inspect size, gauge, finish, flatness
- Test to specification

(p.) Ship

3. Reproducibility Evaluation

Three TDNiCr heats, 3415, 3456 and 3502 were fabricated to 0.025, 0.051 and 0.076 cm.(0.010, 0.020 and 0.030 in.) sheet utilizing the finalized process outlined in detail in the preceding section, "Standard Process 0.025-0.102 cm.(0.010-0.040 in.) Sheet."

Subsequent to rolling each heat to the nominal 0.254 cm. (0.1 in.) intermediate plate gauge, the plates were edge and end sheared. Samples were secured from the offal material at the intermediate gauge for chemical analysis and thoria size determination. The squared plates were then sheared into three equal lengths, one length of each plate being employed for 0.025 cm. (0.010 in.) sheet, one for 0.051 cm.(0.020 in.) sheet and the final piece for 0.076 cm.(0.030 in.) sheet. This resulted in the processing of two (2) sheets of 0.076 x 45.72 x 91.44 cm. (0.030 x 18 x 36 in.), three (3) sheets of 0.051 x 45.72 x 91.44 cm. (0.020 x 18 x 36 in.) and six (6) sheets of 0.025 x 45.72 x 91.44 cm.(0.010 x 18 x 36 in.) from each heat.

Each of these sheets was subjected to a rigid sheet quality evaluation as described elsewhere in this section. Samples were taken from the interior portion of one sheet of each gauge of each heat. Subsequently, the offal material yielded from the shearing of the sheet was sampled on a minimum of two sheets at each gauge

from each heat as shown in Figure 31 and identified as shown in Table 30.

This testing program was carried out in an effort to gain information concerning reproducibility of properties as a function of location within a sheet, sheet to sheet within a heat and heat to heat.

Evaluation of the 45.72 x 91.44 cm. (18 x 36 in.) portion of each sheet was carried out as outlined:

a. Sheet Quality

The sheet quality evaluation of the three gauges from reproducibility heats 3415, 3456 and 3502 was carried out using as the criteria of evaluation Fansteel Specifications S-DMM-S-01-R-0, dated January 1, 1969 and S-TC-S-01-R-1, dated December 1, 1969.

(1.) Gauge Control

Requirement - Paragraph 5.1 of S-DMM-S-01-R-0, dated January 1, 1969.

Thickness		Thickness Tolerance	
cm.	in.	cm.	in.
0.0152-0.025	0.006-0.010, incl.	±0.0038	±0.0015
over 0.025-0.064	0.010-0.025, incl.	±0.0051	±0.002
over 0.064-0.068	0.025-0.034, incl.	±0.0076	±0.003
over 0.068-0.142	0.034-0.056, incl.	±0.0102	±0.004
over 0.142-0.178	0.056-0.070, incl.	±0.0125	±0.005
over 0.178-0.198	0.070-0.078, incl.	±0.0152	±0.006
over 0.198-0.279	0.078-0.109, incl.	±0.0178	±0.007
over 0.279-0.356	0.109-0.140, incl.	±0.0203	±0.008
over 0.356-0.434	0.140-0.171, incl.	±0.0229	±0.009
over 0.434-0.475	0.171-0.187, incl.	±0.025	±0.010

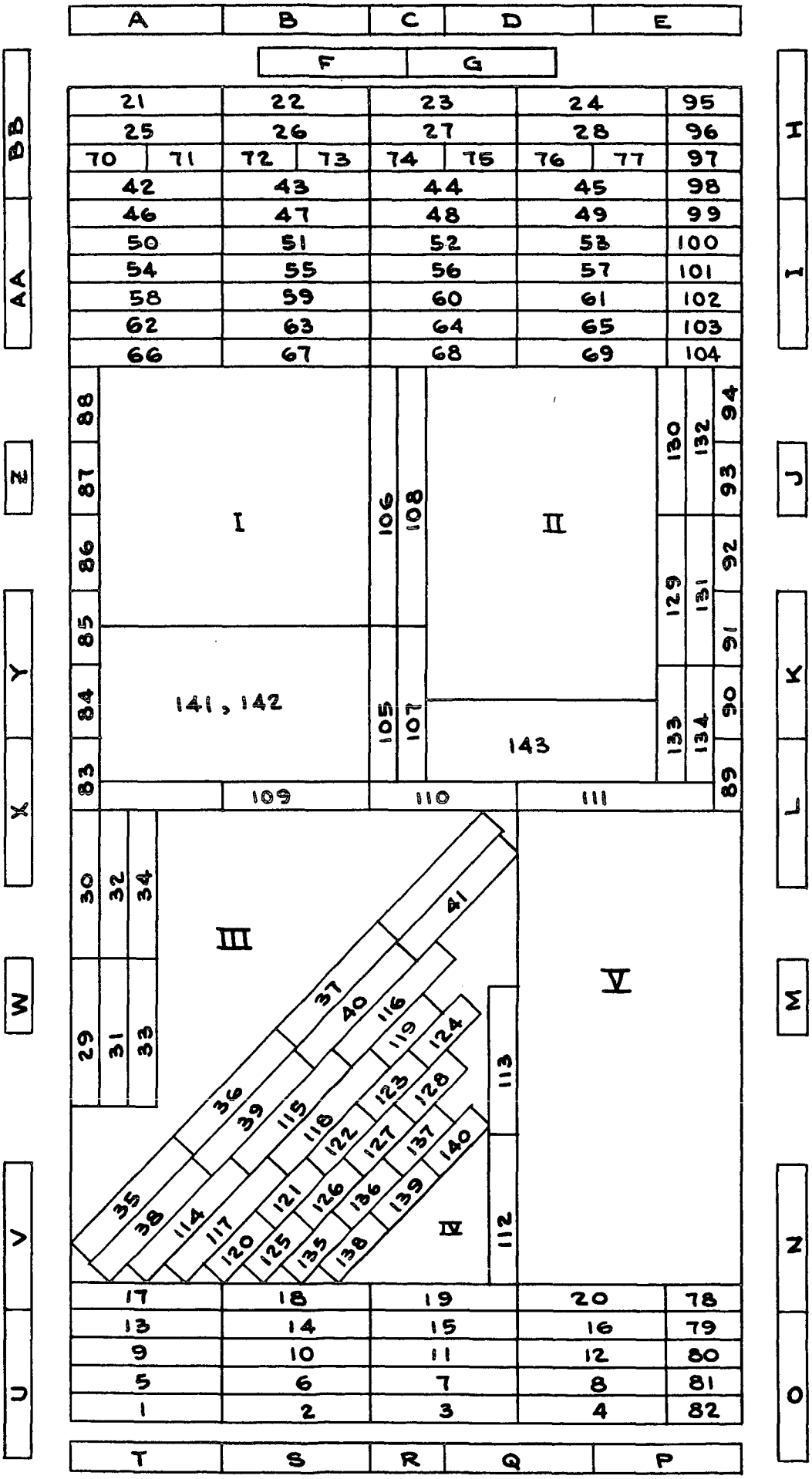


FIGURE 31 - REPRODUCIBILITY TEST PIECE LAYOUT

In accordance with standard commercial practice, thickness measurements are taken at least 0.95 cm.(3/8 in.) from the edge of the sheet.

Each sheet at each gauge from each heat was checked for thickness by vidigage utilizing a 12.7 cm.(5 in.) grid pattern. In addition, each sheet was weighed to determine variance from nominal gauge weight as computed from shet size and TDNiCr theoretical density.

The gauge control data are presented in Tables 31, 32, and 33. As indicated in Tables 31 and 32, the gauge control on all sheets of 0.051 and 0.076 cm.(0.020 and 0.030 in.) sheet of the reproducibility run are well within the required thickness tolerance specified by Fansteel Specification S-DMM-S-01-R-0. In addition, all sheets satisfy a tolerance goal of $\pm$10% of nominal gauge.

It may also be noted from the sheet weight data included in Tables 31 and 32 that only one sheet of 0.076 cm. (0.030 in.) having serial number 502-5 exceeded a goal weight tolerance of plus five percent of theoretical nominal sheet weight. In this particular instance, the deviation could have been corrected by a slightly greater amount of grinding during the finishing operation. Future work will incorporate slightly lower as-rolled gauges for finishing to compensate for this deviation.

Data for the 0.025 cm.(0.010 in.) sheet may be found in Table 33. It may be noted that while total thickness variation in any single sheet does not exceed one-half the total

TABLE 30

REPRODUCIBILITY TESTS

Sample Identification Numbers	Type of Test
A, D, P, S, 1, 2, 109	Transverse-Room Temperature Tensile
H, K, N, V, X, AA, 29, 30, 105, 112	Longitudinal-Room Temperature Tensile
3, 4	Transverse 204°C (400°F) Tensile
5, 6	Transverse 427°C (800°F) Tensile
7, 8	Transverse 649°C (1200°F) Tensile
9, 10	Transverse 871°C (1600°F) Tensile
11, 12	Transverse 982°C (1800°F) Tensile
13, 14, 110, B, E, Q, T	Transverse 1093°C (2000°F) Tensile
15, 16	Transverse 1204°C (2200°F) Tensile
141, 142	Transverse 1316°C (2400°F) Tensile
129, 130	Longitudinal 982°C (1800°F) Tensile
I, L, O, V, Y, BB, 31, 32, 106, 113	Longitudinal 1093°C (2000°F) Tensile
131, 132	Longitudinal 1204°C (2200°F) Tensile
35,36	45° - Room Temperature Tensile
114, 115	45° - 982°C (1800°F) Tensile
37, 38	45° - 1093°C (2000°F) Tensile
116, 117	45° - 1204°C (2200°F) Tensile
17 - 28, 111	Transverse Tensile Spares
33, 34, 107, 108	Longitudinal Tensile Spares
39 - 41, 118	45° Tensile Spares
42 - 69, F, G	Transverse Stress Rupture
70 - 82, 95 - 104, R, C	Transverse Bend
83 - 94, J, M, W, Z	Longitudinal Bend

TABLE 30
(CONT'D)

REPRODUCIBILITY TESTS

Sample Identification Numbers	Type of Test
119 - 128, 135 - 140	45° Bend
133, 134	Oxidation Test - 0.076 cm. (0.030 in.) and 0.025 cm. (0.010 in.) only
I	1204°C (2200°F) Transverse Stress Rupture (Metcut)
II, III, IV, V	Excess Material
143	Preferred Orientation

TABLE 31

GAUGE CONTROL RESULTS OF REPRODUCIBILITY RUN

0.076 cm. SHEET

Heat No.	Nominal Gauge	Sheet Serial No.	Sheet Thickness (cm.) Minimum	Maximum	Total Variation	Theoretical Nominal Sheet Wgt.	Actual Sheet Weight	% Deviation from Nominal
3415	0.076	415-12	0.075	0.082	0.0084	2.68 kg.	2.77 kg.	+3.4
3415	0.076	415-11	0.076	0.084	0.0074	2.68 kg.	2.77 kg.	+3.4
3456	0.076	456-9	0.074	0.081	0.0071	2.68 kg.	2.77 kg.	+3.4
3456	0.076	456-10	0.071	0.080	0.0094	2.68 kg.	2.72 kg.	+1.7
3502	0.076	502-5	0.075	0.082	0.0076	2.68 kg.	2.81 kg.	+5.1
3502	0.076	502-4	0.070	0.079	0.0097	2.68 kg.	2.68 kg.	0

TABLE 31

GAUGE CONTROL RESULTS OF REPRODUCIBILITY RUN

0.030 in. SHEET

Heat No.	Nominal Gauge	Sheet Serial No.	Sheet Thickness (in.) Minimum	Sheet Thickness (in.) Maximum	Total Variation	Theoretical Nominal Sheet Wgt.	Actual Sheet Weight	% Deviation from Nominal
3415	0.030	415-12	0.0296	0.0329	0.0033	5.9 lb.	6.1 lb.	+3.4
3415	0.030	415-11	0.0301	0.0330	0.0029	5.9 lb.	6.1 lb.	+3.4
3456	0.030	456-9	0.0293	0.0321	0.0028	5.9 lb.	6.1 lb.	+3.4
3456	0.030	456-10	0.0282	0.0319	0.0037	5.9 lb.	6.0 lb.	+1.7
3502	0.030	502-5	0.0298	0.0328	0.0030	5.9 lb.	6.2 lb.	+5.1
3502	0.030	502-4	0.0276	0.0314	0.0038	5.9 lb.	5.9 lb.	0

TABLE 32

GAUGE CONTROL RESULTS OF REPRODUCIBILITY RUN

0.051 cm. SHEET

Heat No.	Nominal Gauge	Sheet Serial No.	Sheet Thickness (cm.) Minimum	Sheet Thickness (cm.) Maximum	Total Variation	Theoretical Nominal Sheet Wgt.	Actual Sheet Weight	% Deviation from Nominal
3415	0.051	415-14	0.048	0.056	0.0079	1.81 kg.	1.81 kg.	0
3415	0.051	415-13	0.046	0.051	0.0046	1.81 kg.	1.68 kg.	-7.5
3456	0.051	456-8	0.047	0.051	0.0048	1.81 kg.	1.77 kg.	-2.5
3456	0.051	456-7	0.050	0.054	0.0046	1.81 kg.	1.91 kg.	+5.0
3456	0.051	456-6	0.050	0.055	0.0058	1.81 kg.	1.86 kg.	+2.5
3502	0.051	502-3	0.051	0.056	0.0046	1.81 kg.	1.86 kg.	+2.5
3502	0.051	502-2	0.046	0.055	0.0089	1.81 kg.	1.77 kg.	-2.5
3502	0.051	501-1	0.048	0.053	0.0046	1.81 kg.	1.86 kg.	+2.5

TABLE 32

GAUGE CONTROL RESULTS OF REPRODUCIBILITY RUN

0.020 in. SHEET

Heat No.	Nominal Gauge	Sheet Serial No.	Sheet Thickness (in.) Minimum	Sheet Thickness (in.) Maximum	Total Variation	Theoretical Nominal Sheet Wgt.	Actual Sheet Weight	% Deviation from Nominal
3415	0.020	415-14	0.0189	0.0220	0.0031	4.0 lb.	4.0 lb.	0
3415	0.020	415-13	0.0182	0.0200	0.0018	4.0 lb.	3.7 lb.	-7.5
3456	0.020	456-8	0.0185	0.0204	0.0019	4.0 lb.	3.9 lb.	-2.5
3456	0.020	456-7	0.0196	0.0214	0.0018	4.0 lb.	4.2 lb.	+5.0
3456	0.020	456-6	0.0195	0.0218	0.0023	4.0 lb.	4.1 lb.	+2.5
3502	0.020	502-3	0.0202	0.0220	0.0018	4.0 lb.	4.1 lb.	+2.5
3502	0.020	502-2	0.0181	0.0216	0.0035	4.0 lb.	3.9 lb.	-2.5
3502	0.020	501-1	0.0192	0.0210	0.0018	4.0 lb.	4.1 lb.	+2.5

TABLE 33

GAUGE CONTROL RESULTS OF REPRODUCIBILITY RUN

0.025 cm. SHEET

Heat No.	Nominal Gauge	Sheet Serial No.	Sheet Thickness (cm.) Minimum	Sheet Thickness (cm.) Maximum	Total Variation	Theoretical Nominal Sheet Wgt.	Actual Sheet Weight	% Deviation from Nominal
3415	0.025	415-16	0.0224	0.0259	0.0038	.87 kg.	.85 kg.	-5.1
3415	0.025	415-17	0.0249	0.0277	0.0028	.87 kg.	.92 kg.	+5.1
3415	0.025	415-C				.87 kg.	.87 kg.	+0.5
3456	0.025	456-18	0.0259	0.0290	0.0030	.87 kg.	1.01 kg.	+13.1
3456	0.025	456-19	0.0282	0.0291	0.0012	.87 kg.	1.01 kg.	+11.6
3456	0.025	456-D				.87 kg.	.91 kg.	+ 4.1
3502	0.025	502-20	0.0259	0.0286	0.0025	.87 kg.	.96 kg.	+ 9.6
3502	0.025	502-21	0.0216	0.0251	0.0036	.87 kg.	.83 kg.	- 5.1
3502	0.025	502-D				.87 kg.	.87 kg.	- 0.5

TABLE 33

GAUGE CONTROL RESULTS OF REPRODUCIBILITY RUN

0.010 in. SHEET

Heat No.	Nominal Gauge	Sheet Serial No.	Sheet Thickness (in.) Minimum	Sheet Thickness (in.) Maximum	Total Variation	Theoretical Nominal Sheet Wgt.	Actual Sheet Weight	% Deviation from Nominal
3415	0.010	415-16	0.0088	0.0103	0.0015	1.98 lb.	1.88 lb.	-5.1
3415	0.010	415-17	0.0098	0.0109	0.0011	1.98 lb.	2.08 lb.	+5.1
3415	0.010	415-C				1.98 lb.	1.99 lb.	+0.5
3456	0.010	456-18	0.0103	0.0115	0.0012	1.98 lb.	2.24 lb.	+13.1
3456	0.010	456-19	0.0111	0.0116	0.0005	1.98 lb.	2.21 lb.	+11.6
3456	0.010	456-D				1.98 lb.	2.06 lb.	+4.1
3502	0.010	502-20	0.0103	0.0113	0.0010	1.98 lb.	2.17 lb.	+9.6
3502	0.010	502-21	0.0085	0.0099	0.0014	1.98 lb.	1.88 lb.	-5.1
3502	0.010	502-D				1.98 lb.	1.97 lb.	-0.5

thickness variation allowed by the specification, the thickness variation from sheet to sheet appears to cover the entire allowable variation. Further, one sheet, 456-19 from Heat 3456 was found to be 0.0002 cm.(0.0001 in.) over tolerance in one area. Finally, four of the nine sheets evaluated for weight tolerance were found to exceed the goal weight tolerance of plus five percent of theoretical nominal sheet weight.

The difficulties encountered on the 0.025 cm. (0.010 in.) reproducibility sheet were attributed to the material being processed during the early stages of the learning curve for the finishing procedure identified as the cold rolled annealed finish. It is anticipated that the warm rolling can be controlled more closely to yield 0.025 cm.(0.010 in.) unrecrystallized sheet at a thickness approaching nominal or slightly less, thus satisfying goal weight tolerance requirements.

In addition, it should be pointed out that cold finish rolling was accomplished by hand rolling on all reproducibility material. Present processing has replaced hand rolling with tension rolling which improves both gauge control and flatness and is a "must-process" in order to scale up sheet sizes from 45.72 x 91.44 cm.(18 x 36 in.) to 60.96 x 152.40 cm. (24 x 60 in.). An example of gauge and weight control obtained employing these techniques is shown with Heat 3694 in Table 34. These data demonstrate that the goal weight tolerance can be met.

(2.) Flatness

Requirement - Paragraph 5.4 of S-DMM-S-01-R-0, dated January 1, 1969.

Flatness Tolerance: The maximum deviation from flatness shall not exceed 8% as calculated from the following formula:

$$\frac{H}{L} \times 100 = \% \text{ Flatness Deviation}$$

where: H = Maximum vertical distance between a flat reference surface and the lower surface of the sheet;

L = Minimum horizontal distance between the high point on the sheet where H is determined and the point where the lower surface of the sheet touches the reference surface.

A value of H less than 0.158 cm.(1/16 in.) shall not be cause for rejection. The maximum deviation from flatness shall not exceed 5.08 cm.(2 in.), independent of span, as measured with the sheet resting concave side down on a flat reference surface.

Each sheet at each gauge from each heat was checked for flatness as specified in the above requirement. The resultant data are presented in Table 35. As these data indicate, all the sheets from the reproducibility run satisfied the 8 percent deviation from flatness except sheets 415-12 and 502-20 which were 11.1 percent and 8.9 percent out of flatness. Each of these sheets were subjected to room temperature roll leveling and the deviation from flatness on sheet 415-12 was reduced from 11.1 percent to 5.1 percent, while sheet 502-20 showed no change as a result of roll leveling. These results verified previously reported work carried out on effect of room temperature roll leveling of

TABLE 34

GAUGE CONTROL RESULTS WITH IMPROVED PRACTICE

0.025 cm. SHEET

Heat No.	Nominal Gauge cm.	Sheet Serial No.	Sheet Thickness (cm.) Minimum	Sheet Thickness (cm.) Maximum	Total Variation	Theoretical Nominal Sheet Wgt.	Actual Sheet Weight	% Deviation from Nominal
3694	0.025	479	0.0221	0.0249	0.0028	1.86 kg.	1.72 kg.	-7.3
3694	0.025	478	0.0241	0.0265	0.0025	1.81 kg.	1.72 kg.	-2.5
3694	0.025	476A	0.0249	0.0256	0.0010	1.13 kg.	1.13 kg.	0
3694	0.025	477A	0.0234	0.0253	0.0023	1.04 kg.	1.00 kg.	-4.4
3694	0.025	476B	0.0251	0.0265	0.0015	.59 kg.	.59 kg.	0
3694	0.025	477B	0.0241	0.0268	0.0028	.68 kg.	.68 kg.	0
3694	0.025	475	0.0251	0.0271	0.0020	1.81 kg.	1.86 kg.	+2.5
3694	0.025	474	0.0246	0.0265	0.0020	1.72 kg.	1.72 kg.	0
3694	0.025	473	0.0244	0.0274	0.0030	1.72 kg.	1.68 kg.	-2.6

TABLE 34

GAUGE CONTROL RESULTS WITH IMPROVED PRACTICE

0.010 in. SHEET

Heat No.	Nominal Gauge in.	Sheet Serial No.	Sheet Thickness (in.) Minimum	Maximum	Total Variation	Theoretical Nominal Sheet Wgt.	Actual Sheet Weight	% Deviation from Nominal
3694	0.010	479	0.0087	0.0098	0.0011	4.1 lb.	3.8 lb.	-7.3
3694	0.010	478	0.0095	0.0105	0.0010	4.0 lb.	3.9 lb.	-2.5
3694	0.010	476A	0.0098	0.0102	0.0004	2.5 lb.	2.5 lb.	0
3694	0.010	477A	0.0092	0.0101	0.0009	2.3 lb.	2.2 lb.	-4.4
3694	0.010	476B	0.0099	0.0105	0.0006	1.3 lb.	1.3 lb.	0
3694	0.010	477B	0.0095	0.0106	0.0011	1.5 lb.	1.5 lb.	0
3694	0.010	475	0.0099	0.0107	0.0008	4.0 lb.	4.1 lb.	+2.5
3694	0.010	474	0.0097	0.0105	0.0008	3.8 lb.	3.8 lb.	0
3694	0.010	473	0.0096	0.0108	0.0012	3.8 lb.	3.7 lb.	-2.6

TABLE 35

FLATNESS RESULTS OF REPRODUCIBILITY RUN

Heat No.	Nominal Gauge cm.	Nominal Gauge in.	Sheet Serial No.	% Deviation from Flatness As Rolled	% Deviation from Flatness After Roll Leveling
3415	0.025	0.010	415-17	7.6	
3415	0.025	0.010	415-16	6.7	
3415	0.051	0.020	415-14	2.9	
3415	0.051	0.020	415-13	1.8	
3415	0.076	0.030	415-12	11.1	5.1
3415	0.076	0.030	415-11	7.4	
3456	0.025	0.010	456-19	6.1	
3456	0.025	0.010	456-18	5.2	
3456	0.051	0.020	456-8	2.3	
3456	0.051	0.020	456-7	3.1	
3456	0.051	0.020	456-6	2.8	
3456	0.076	0.030	456-9	4.5	
3456	0.076	0.030	456-10	4.1	
3502	0.025	0.010	502-21	6.2	
3502	0.025	0.010	502-20	8.9	8.9
3502	0.051	0.020	502-3	2.1	
3502	0.051	0.020	502-2	4.7	
3502	0.051	0.020	502-1	2.5	
3502	0.076	0.030	502-4	2.6	
3502	0.076	0.030	502-5	3.1	

TDNiCr sheet. Roll leveling appears to be beneficial on gauges greater than 0.051 cm.(0.020 in.) thickness but shows little if any improvement on sheet less than 0.051 cm.(0.020 in.) thickness. It is necessary to employ cold tension rolling on sheet less than 0.051 cm.(0.020 in.) thickness in order to satisfy the 8 percent requirement and also the goal requirement of 6 percent.

(3.) Surface Finish

While not presently a requirement in either S-DMM-S-01-R-0 or S-TC-S-01-R-1, data were collected for future use. Working toward a goal of a surface finish of 32 rms or better, the 0.051 and 0.076 cm.(0.020 and 0.030 in.) sheets from the reproducibility run were all abrasively ground finished. As shown in Table 36, all sheets were found to be better than the 32 rms finish required in both longitudinal and transverse directions.

Better finishes than 32 rms may also be attained by the abrasive grinding and polishing technique. Finish requirements are governed primarily by total labor applied.

Similarly, the surface finish of the 0.025 cm. (0.010 in.) sheets which were cold rolled-annealed finished were also evaluated. These results are shown in Table 37. As indicated by these data, the goal finish of 32 rms is handily satisfied employing the cold rolled-annealed finish on 0.025 cm.(0.010 in.) sheet. These finishes are also subject to change as a result of roll finish and/or percent reduction by cold work up to a maximum of 20 percent.

TABLE 36

REPRODUCIBILITY RUN SURFACE FINISH RESULTS

Abrasively Ground Finished 0.051 cm.-0.076 cm. (0.020-0.030) in.) Sheet

Heat No.	Nominal Gauge cm.	Nominal Gauge in.	Sheet Serial No.	rms Finish Side 1 Long.	rms Finish Side 1 Trans.	rms Finish Side 2 Long.	rms Finish Side 2 Trans.
3415	0.051	0.020	415-14	9-11	14-16	8-10	19-23
3415	0.051	0.020	415-13	8-10	20-25	6-8	18-23
3415	0.076	0.030	415-12	10-13	25-30	9-11	25-30
3415	0.076	0.030	415-11	7-10	16-20	6-9	17-20
3456	0.051	0.020	456-8	6-9	17-20	10-14	22-26
3456	0.051	0.020	456-7	6-8	16-19	6-8	14-17
3456	0.051	0.020	456-6	7-9	18-21	7-10	20-22
3456	0.076	0.030	456-9	9-12	23-27	6-17	17-20
3456	0.076	0.030	456-10	8-10	19-22	8-10	20-23
3502	0.051	0.020	502-3	15-18	22-25	13-15	25-27
3502	0.051	0.020	502-2	10-13	24-27	13-15	25-27
3502	0.051	0.020	502-1	8-10	22-23	6-8	18-20
3502	0.076	0.030	502-5	7-9	18-20	7-9	17-20
3502	0.076	0.030	502-4	12-15	20-22	11-14	23-26

TABLE 37

REPRODUCIBILITY RUN SURFACE FINISH RESULTS
COLD ROLLED-ANNEALED FINISHED 0.025 cm. (0.010 in.) SHEET

Heat No.	Nominal Gauge cm.	Nominal Gauge in.	Sheet Serial No.	rms Finish Side 1 Long.	rms Finish Side 1 Trans.	rms Finish Side 2 Long.	rms Finish Side 2 Trans.
3415	0.025	0.010	415-17	15-20	13-16	17-21	18-23
3415	0.025	0.010	415-16	20-25	18-21	14-16	19-24
3456	0.025	0.010	456-19	17-19	15-17	16-19	16-19
3456	0.025	0.010	456-18	14-17	13-15	14-16	16-20
3502	0.025	0.010	502-21	16-17	16-19	17-20	16-20
3502	0.025	0.010	502-20	15-17	14-17	15-18	14-18

(4.) Integrity

Each sheet at each gauge from each heat was subjected to vidigage checking during thickness evaluation. This testing technique also indicates the presence of laminations or internal defects. In addition to the final sheet samples, numerous samples were secured during processing at all stages for metallographical evaluation.

During all evaluation, no indications of macro or micro defects were encountered.

(5.) Chemistry

Requirement - Paragraph 2.1 of S-TC-S-01-R-1, dated December 1, 1969.

The chemical composition, as determined by Fansteel standard analytical procedures, shall conform to the following limits:

Constituent	Minimum Weight Percent	Maximum Weight Percent	Check Analysis Weight Percent
Thoria(ThO_2)	1.50	3.00	$\pm$0.1
Chromium	18.00	22.00	$\pm$0.2
Carbon		0.05	$\pm$0.005
Sulfur		0.015	$\pm$0.002
Nickel	By Difference		

Check analysis limits provide for sampling and between laboratory variability. Customer analyses which differ from the specification limits by less than the check analysis tolerance shall not be cause for rejection.

Specimens from each heat were secured at the nominal 0.254 cm.(0.1 in.) intermediate plate stage of processing and tested in the recrystallized condition.

The resultant data are presented in Table 38. The chemical compositions of the reproducibility heats were well within requirements and also satisfied specification goals which were as follows:

Chemical Composition

ThO_2 - 1.80 - 2.60%

Cr - 19.00 - 21.00%

C - 0.03% maximum

S - 0.01% maximum

(6.) Metallography

Metallographic examination by light microscopy was conducted on one sheet of each heat and gauge of the reproducibility series of TDNiCr. Samples numbers 18 and 108 shown in Figure 31 were utilized.

The samples for light microscopy were prepared using the procedures given in Appendix B.

Photomicrographs were taken of the two areas in both the longitudinal and transverse sections at an appropriate magnification. The line intercept technique was then used to measure average grain size and grain aspect ratio, see Appendix B.

Table 39 is a summary of the average grain sizes and grain aspect ratios for each heat and gauge in both longitudinal and transverse directions. Generally, each gauge of all

TABLE 38

CHEMICAL ANALYSIS DATA

Constituent	Heat No. 3415 Wt. %	Heat No. 3456 Wt. %	Heat No. 3502 Wt. %
Thoria (ThO_2)	2.060	2.170	2.110
Chromium	19.490	19.450	19.660
Carbon	.017	.029	.029
Sulfur	.003	.002	.003
Nickel	Bal.	Bal.	Bal.

TABLE 39

AVERAGE GRAIN SIZES OF REPRODUCIBILITY HEATS

Heat No.	Gauge cm.	Gauge in.	Direction	Grain Size mm	Aspect Ratio α
3415	0.076	0.030	Longitudinal	0.048	3.5
3415	0.076	0.030	Transverse	0.044	2.9
3456	0.076	0.030	Longitudinal	0.116	5.3
3456	0.076	0.030	Transverse	0.118	4.6
3502	0.076	0.030	Longitudinal	0.052	3.7
3502	0.076	0.030	Transverse	0.044	2.8
3415	0.051	0.020	Longitudinal	0.075	3.2
3415	0.051	0.020	Transverse	0.063	2.5
3456	0.051	0.020	Longitudinal	0.052	3.5
3456	0.051	0.020	Transverse	0.048	3.4
3502	0.051	0.020	Longitudinal	0.071	3.1
3502	0.051	0.020	Transverse	0.064	2.5
3415	0.025	0.010	Longitudinal	0.082	3.2
3415	0.025	0.010	Transverse	0.075	2.8
3456	0.025	0.010	Longitudinal	0.090	4.2
3456	0.025	0.010	Transverse	0.097	2.4
3502	0.025	0.010	Longitudinal	0.082	3.8
3502	0.025	0.010	Transverse	0.091	3.9

heats had similar grain sizes. The 0.076 cm.(0.030 in.) gauge for Heat 3456, however, had a significantly larger grain size and grain aspect ratio than the other heats.

A progressive increase in grain size is noted as the gauge is reduced. Typical values for 0.076 cm.(0.030 in.) material, excluding Heat 3456, are approximately 0.047 mm. At 0.051 cm.(0.020 in.) and 0.025 cm.(0.010 in.), typical values are 0.060 mm and 0.085 mm respectively. There is no difference between the average grain size when viewed in the longitudinal or the transverse direction: the average grain sizes in the longitudinal and transverse directions for all heats and gauges are 0.074 and 0.072 mm respectively.

Grain aspect ratios are somewhat higher in the longitudinal direction. An average value of 3.75 was measured for longitudinal and 3.16 for transverse.

The reason for the somewhat larger grain size of Heat 3456 at 0.076 cm.(0.030 in.) is not known. However, subsequent evaluation of its effects on mechanical properties, which is reviewed in the following sections, shows that it has only minor effects on some of the mechanical properties.

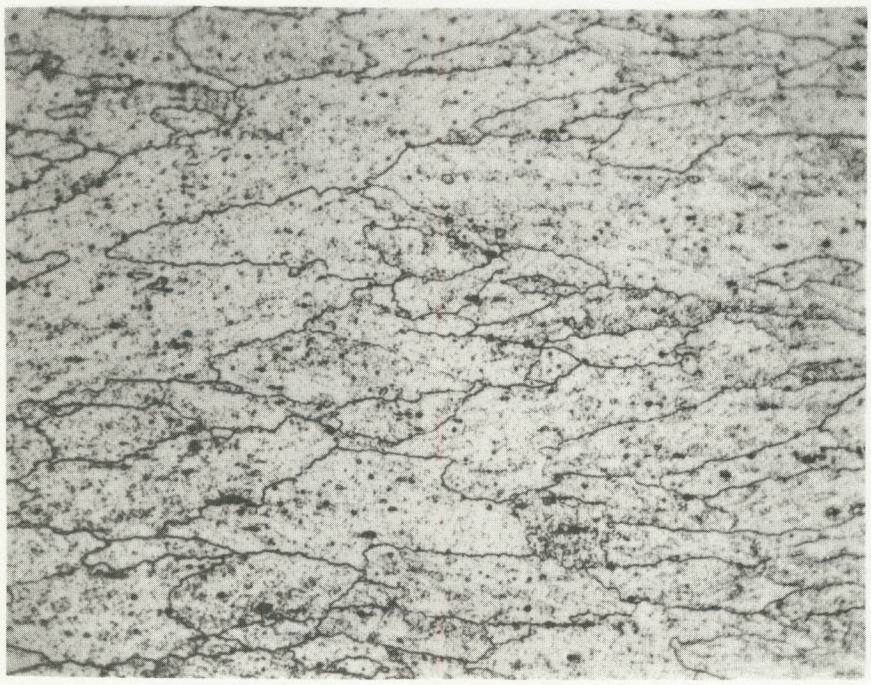
Figures 32, 33 and 34 contain longitudinal and transverse photomicrographs of 0.076, 0.051 and 0.025 cm.(0.030, 0.020 and 0.010 in.) sheet which are typical for each gauge.

Thoria and Cr_2O_3 distribution were examined by replication electron microscopy on a Bendix Tronscope. The replication technique is given in Appendix B. Figure 35 shows



HEAT 3415
0.076 cm.(0.030 in.)
LONGITUDINAL
SECTION

250X

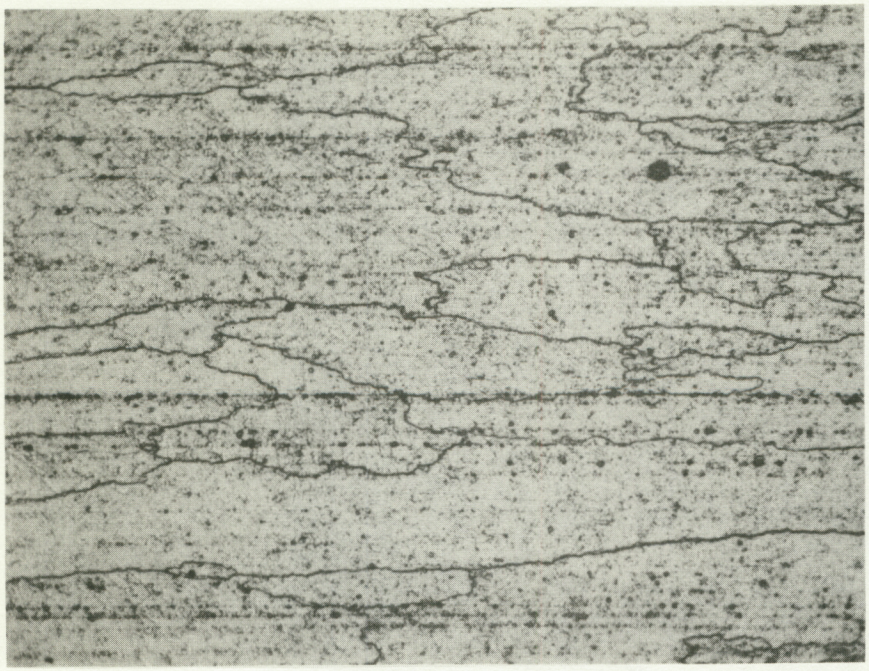


HEAT 3415
0.076 cm (0.030 in.)
TRANSVERSE
SECTION

250X

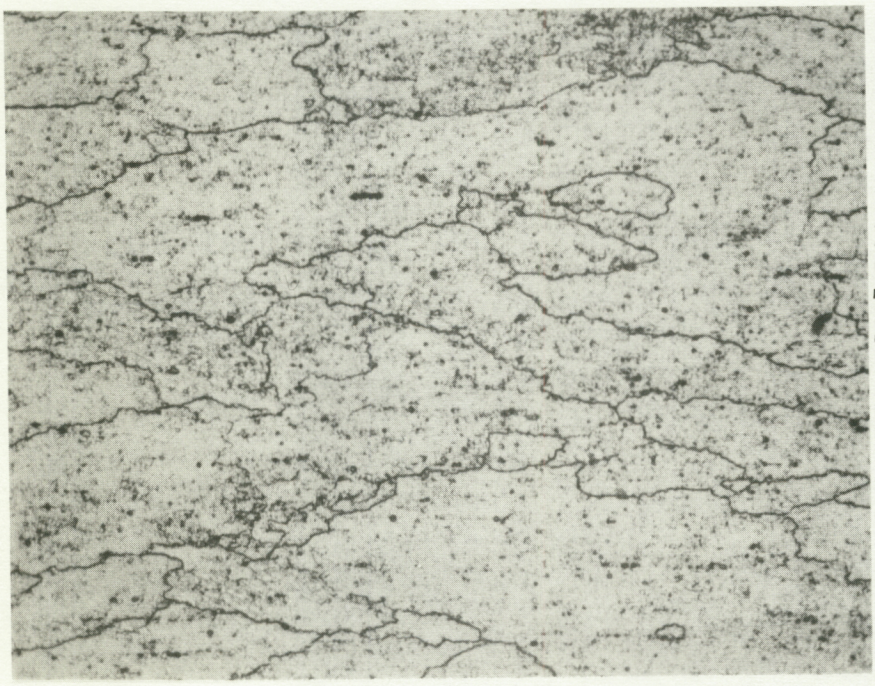
FIGURE 32

TYPICAL MICROSTRUCTURE OF 0.076 cm.(0.030 in.) TDNiCr SHEET, EXCLUDING HEAT 3456



HEAT 3415,
0.051 cm.(0.020 in.)
LONGITUDINAL
SECTION

250X

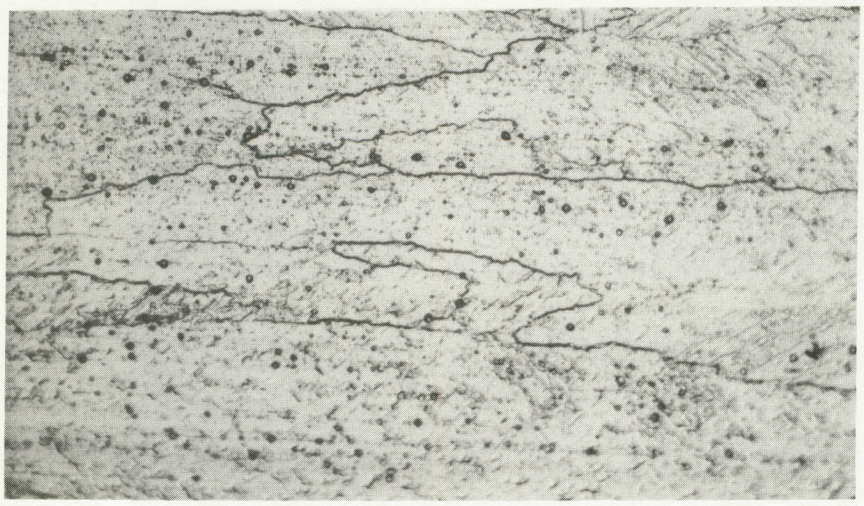


HEAT 3415,
0.051 cm.(0.020 in.)
TRANSVERSE
SECTION

250X

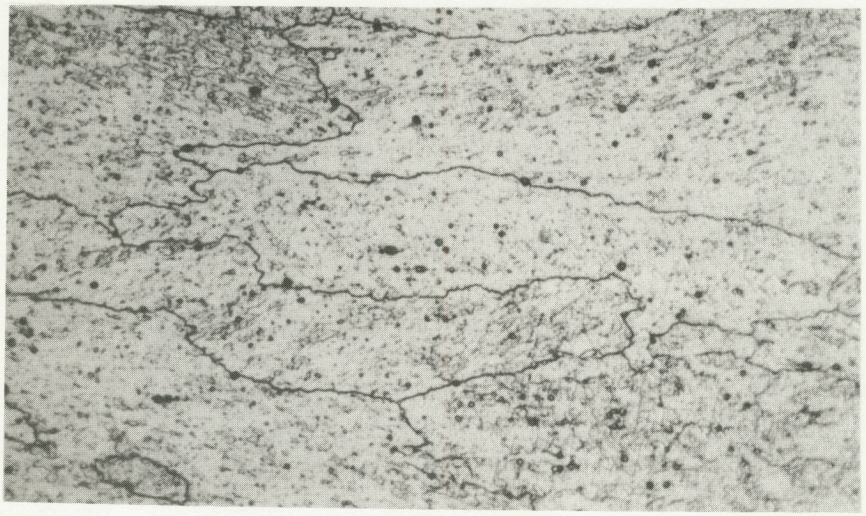
FIGURE 33

TYPICAL MICROSTRUCTURE FOR 0.051 cm.(0.020 in.) TDNiCr SHEET



Heat 3456
0.025 cm.
(0.010 in.)
Longitudinal
Section

250X

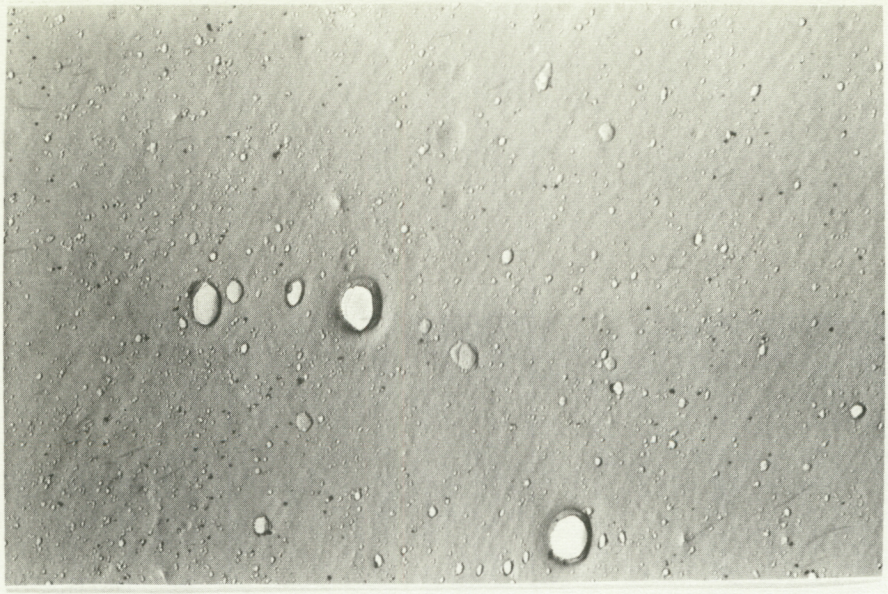


Heat 3456
0.025 cm.
(0.010 in.)
Transverse
Section

250X

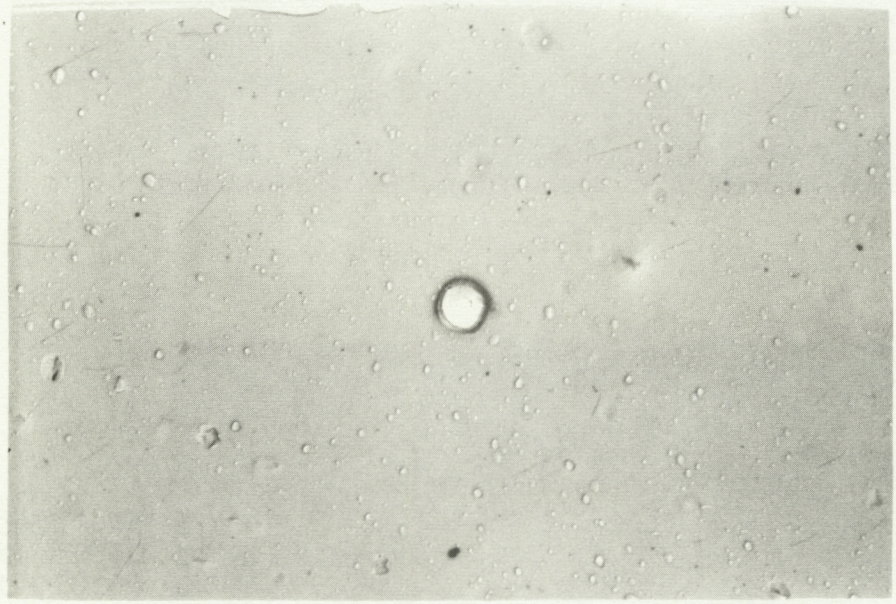
FIGURE 34

TYPICAL MICROSTRUCTURE OF 0.025 cm .(0.010 in.) TDNiCr SHEET



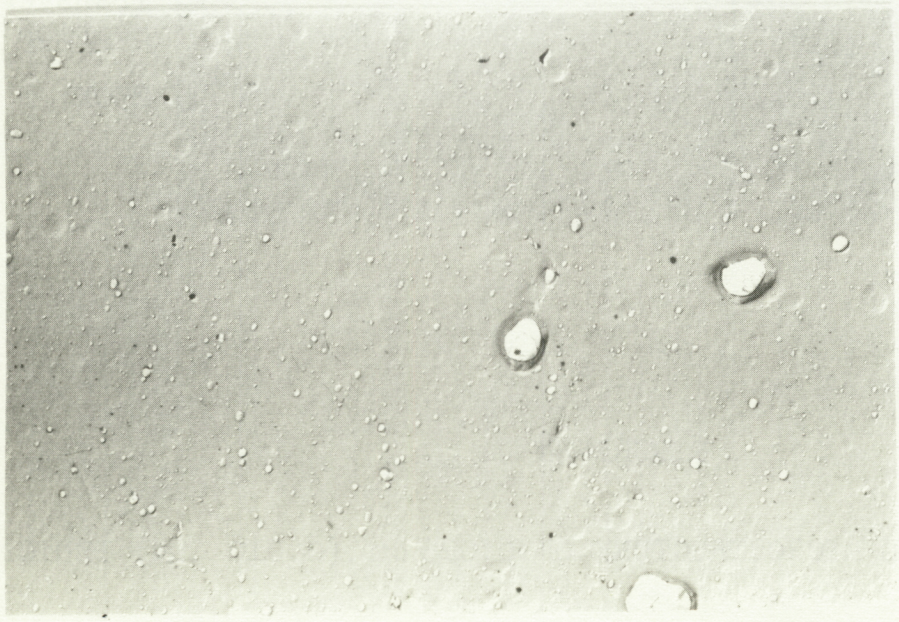
HEAT 3415
0.051 cm.
(0.020 in.)

Planar
Section
10,000 X



HEAT 3415
0.051 cm.
(0.020 in.)

Planar
Section
10,000 X



HEAT 3502
0.051 cm.
(0.020 in.)

Planar
Section
10,000 X

FIGURE 35 - ELECTRON PHOTOMICROGRAPH OF ThO_2 AND Cr_2O_3 DISTRIBUTION IN REPRODUCIBILITY HEATS

representative sections from each heat at 0.051 cm.(0.020 in.). Thoria particles appear as either small white or black areas, the black areas corresponding to ThO_2 which has "pulled out" during replication. Cr_2O_3 appears as significantly larger white particles ranging in diameter from 0.1 micron to 1.0 micron. There is no apparent difference between any of the heats in either thoria or Cr_2O_3 distribution.

b. Mechanical Properties

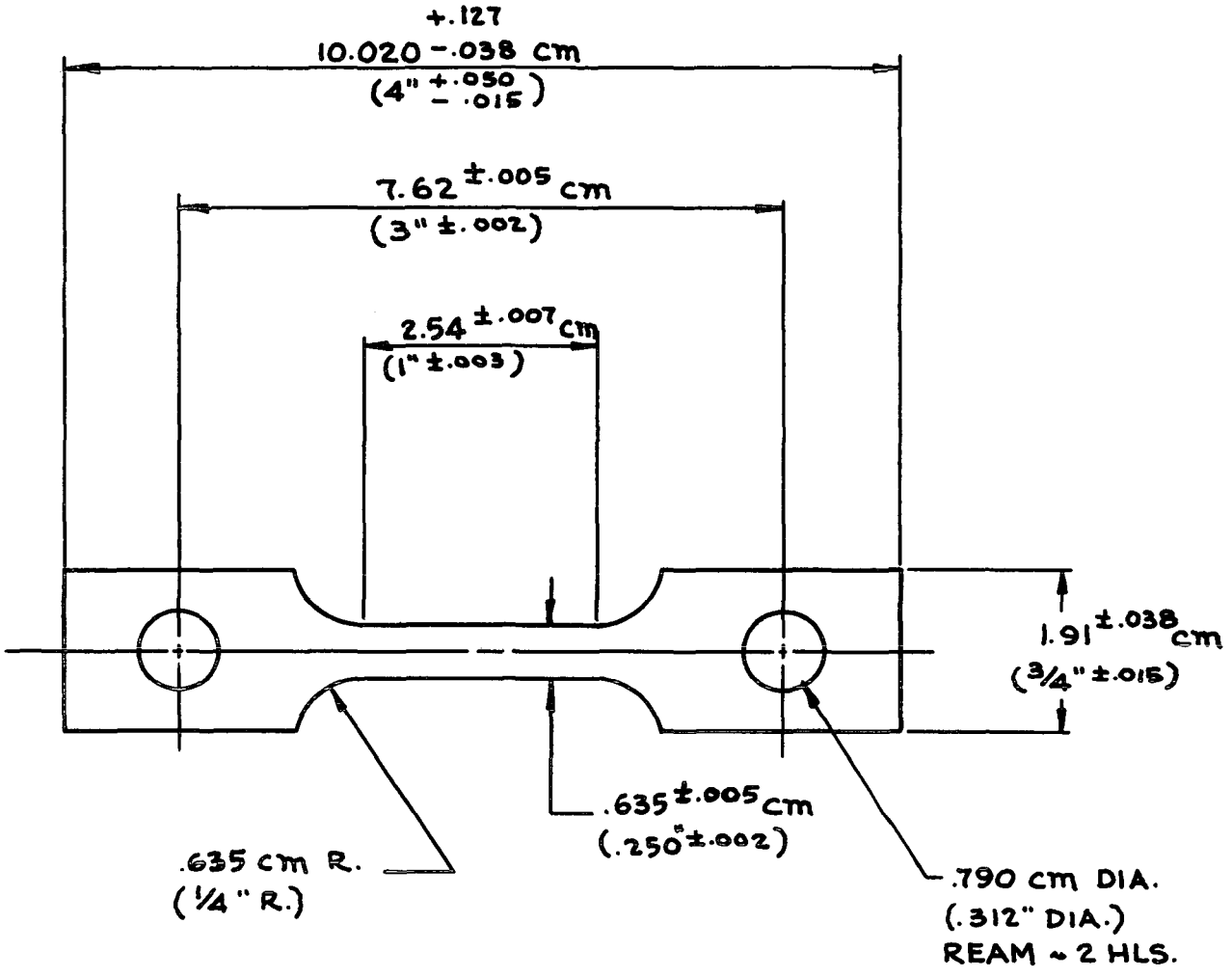
An extensive evaluation of the mechanical property reproducibility of Heats 3415, 3456 and 3502 was conducted. One 45.72 x 91.44 cm.(18 x 36 in.) sheet at each gauge from each heat was sectioned and identified according to the layout in Figure 31 and Table 30. In addition, test samples from the offal material were sampled on a minimum of two sheets for each gauge and heat. Individual test data are given in Appendix C.

(1.) Tensile Properties

Tensile properties were examined as a function of temperature, location within a sheet, orientation with respect to the rolling direction, gauge, heat, and sheet. In addition, means, standard deviations, and 95 and 99.7% probability bands were calculated for the 1093°C(2000°F) tensile strength.

The specimen configuration shown in Figure 36 was utilized for all tensile testing.

Room and elevated temperature tests were performed on a Baldwin 267,000 N (60,000 lb.) hydraulic universal testing machine. Room temperature tests were conducted at a strain rate



NOTES:

1. HOLES WITHIN ±.005 cm (±.002") OF TEST SECTION CENTERLINE.
2. TEST SECTION ~ NO UNDERCUTTING OR TAPER.

FIGURE 36

TENSILE SPECIMEN

of 0.005 cm/cm/min. (0.005 in/in/min.) to yield and at a cross head speed of 0.05 cm/cm/min. (0.05 in/in/min.) to fracture. Elevated temperature tests were conducted at a cross head speed of 0.05 cm/cm/min. (0.05 in/in/min.).

Percent elongations were measured by the "fit back" technique, whereby the increase in distance between scribe marks on the specimen is the plastic deformation which has occurred in testing.

Comments relative to each of the variables previously mentioned follow:

(a.) Temperature

Tensile tests were conducted at various temperatures to determine the temperature dependence of the ultimate and yield strengths of TDNiCr. Each heat and each gauge of the reproducibility series were utilized. Test specimen identification was as follows.

R.T.	R.T.	-	Trans.	Sample	#1, #2 and #109
204°C	400°F	-	"	"	#3 and #4
427	800	-	"	"	#5 and #6
649	1200	-	"	"	#7 and #8
871	1600	-	"	"	#9 and #10
982	1800	-	"	"	#11 and #12
1093	2000	-	"	"	#13, #14 and #110
1204	2200	-	"	"	#15 and #16
1316	2400	-	"	"	#141 and #142
Spares		-	"	"	Samples #17 thru #28

Figures 37, 38, 39 and 40 are graphs of the transverse ultimate and yield strengths for 0.051 cm.(0.020 in.) and 0.076 cm. (0.030 in.) sheet, and 0.025 cm.(0.010 in.) sheet as a function of temperature. The 0.025 cm.(0.010 in.) sheet has been treated separately because of the lower strengths typically observed for this gauge. Also, Fansteel Specification S-TC-S-01-R-1 for TDNiCr requires higher room temperature and 1093°C(2000°F) strengths for sheet thickness greater than nominal 0.048 cm. (0.019 in.).

Typical ultimate strength values for the 982°C, 1093°C and 1204°C(1800°F, 2000°F and 2200°F) temperatures were approximately 158.8, 132.0 and 93.0 MN/m^2 (23.0, 19.0 and 13.5 ksi) respectively. Strengthening effect of chromium in solid solution is diminished rapidly in the 427-871°C(800-1600°F) temperature range. As the temperature is increased the values of the ultimate and yield strengths converge. At room temperature there is approximately a 33% difference between ultimate and yield and, at 1093°C(2000°F) a 0.7% difference.

Percent elongations were also measured at each temperature. It was found that above 427°C(800°F), a marked decrease in ductility occurred, from a 20% average at 427°C(800°F) to a 6% average at 649°C(1200°F). Metallographic examination of fractured tensile specimens revealed that the mode of fracture changed from transgranular to intergranular between these two temperatures; that is, the equicohesive temperature is between 427°C and 649°C(800°F and 1200°F). Percent elongations (Figures 41 and 42) in the 982°C to 1204°C(1800°F to 2200°F) range were 1.0 to 7.5%.

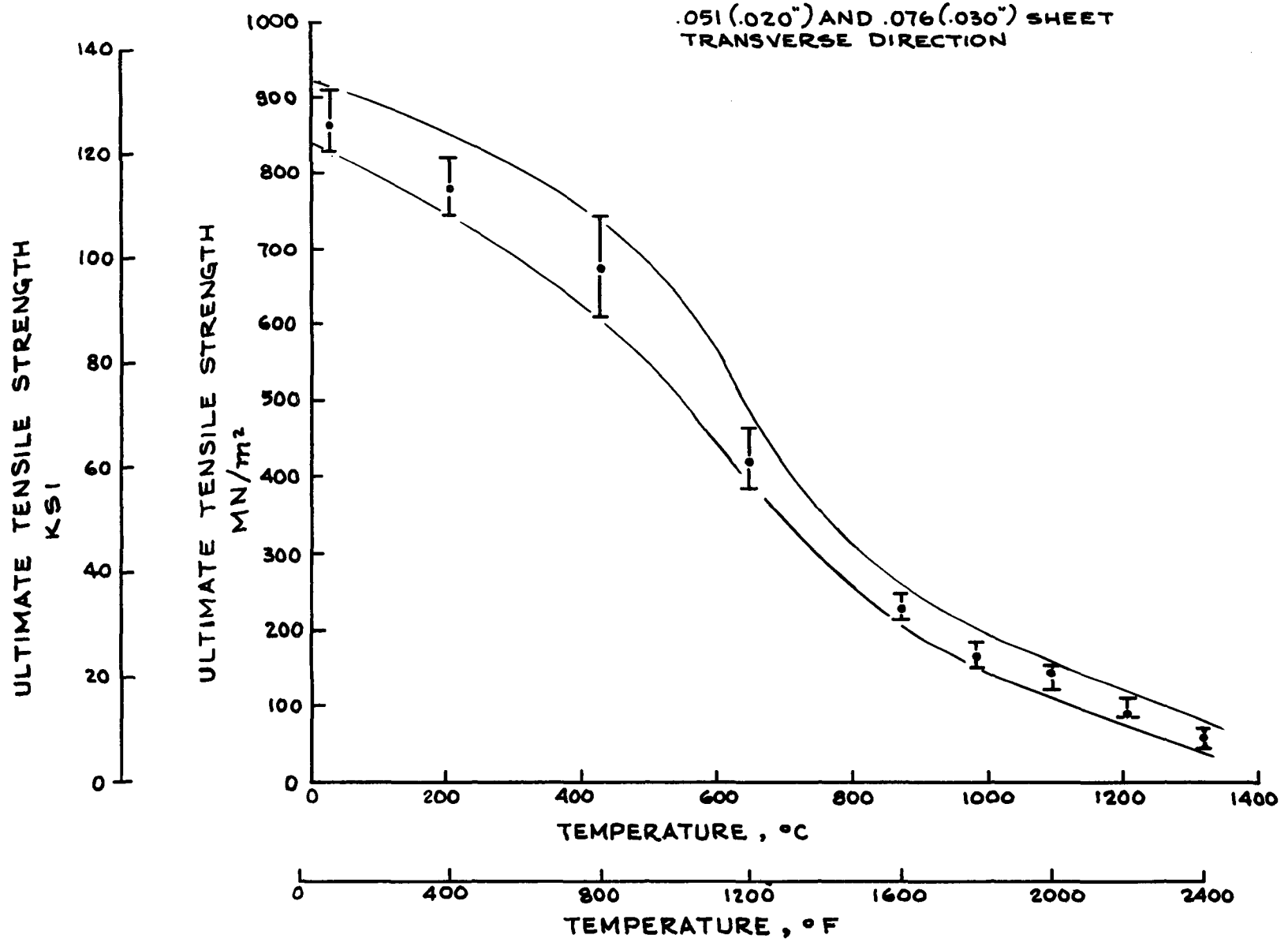


FIGURE 37. ULTIMATE TENSILE STRENGTH AS A FUNCTION OF TEMPERATURE FOR TDNiCr SHEET

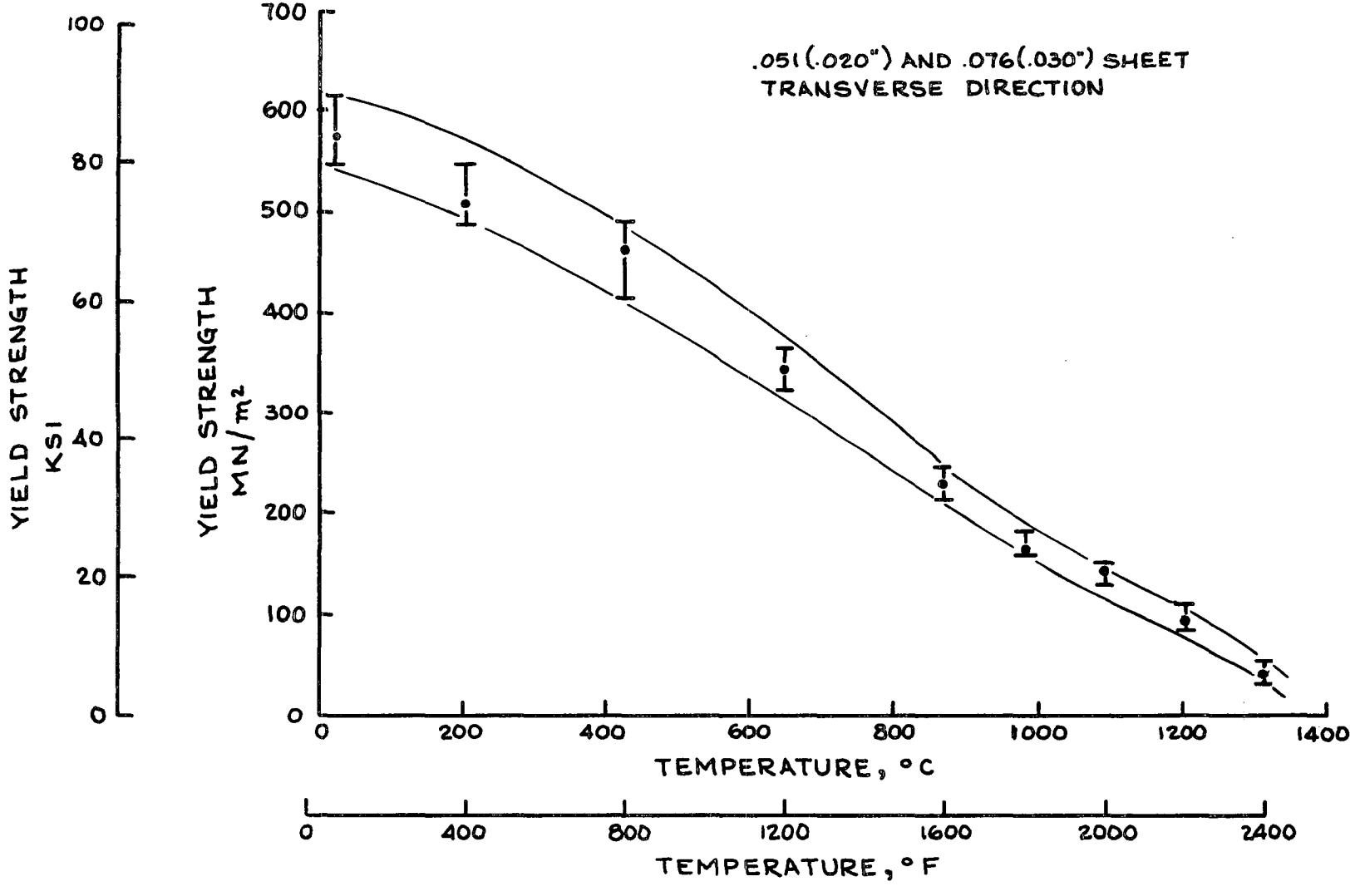


FIGURE 38. YIELD STRENGTH AS A FUNCTION OF TEMPERATURE FOR TDNiCr SHEET

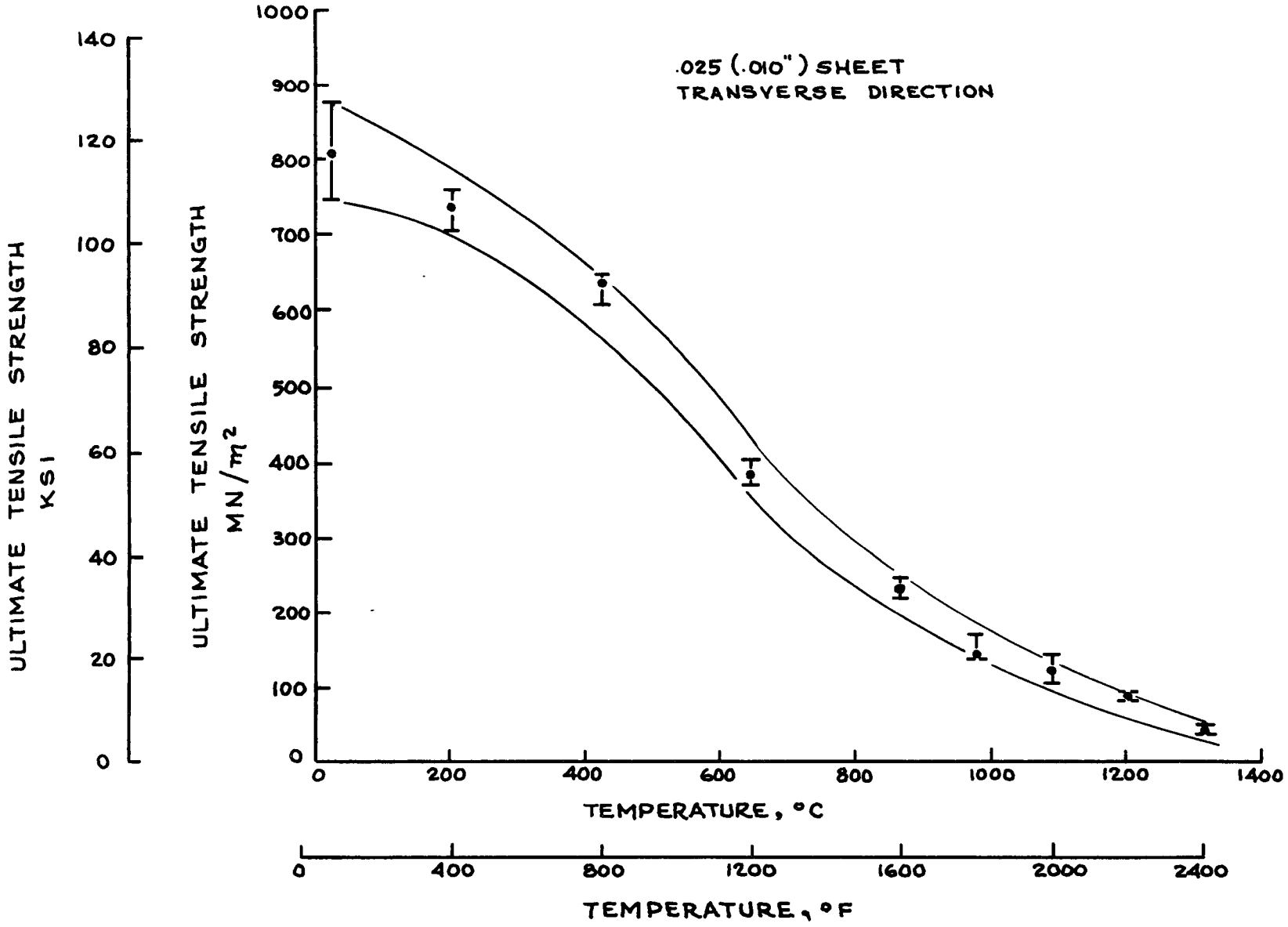


FIGURE 39. ULTIMATE TENSILE STRENGTH AS A FUNCTION OF TEMPERATURE FOR TDNiCr SHEET

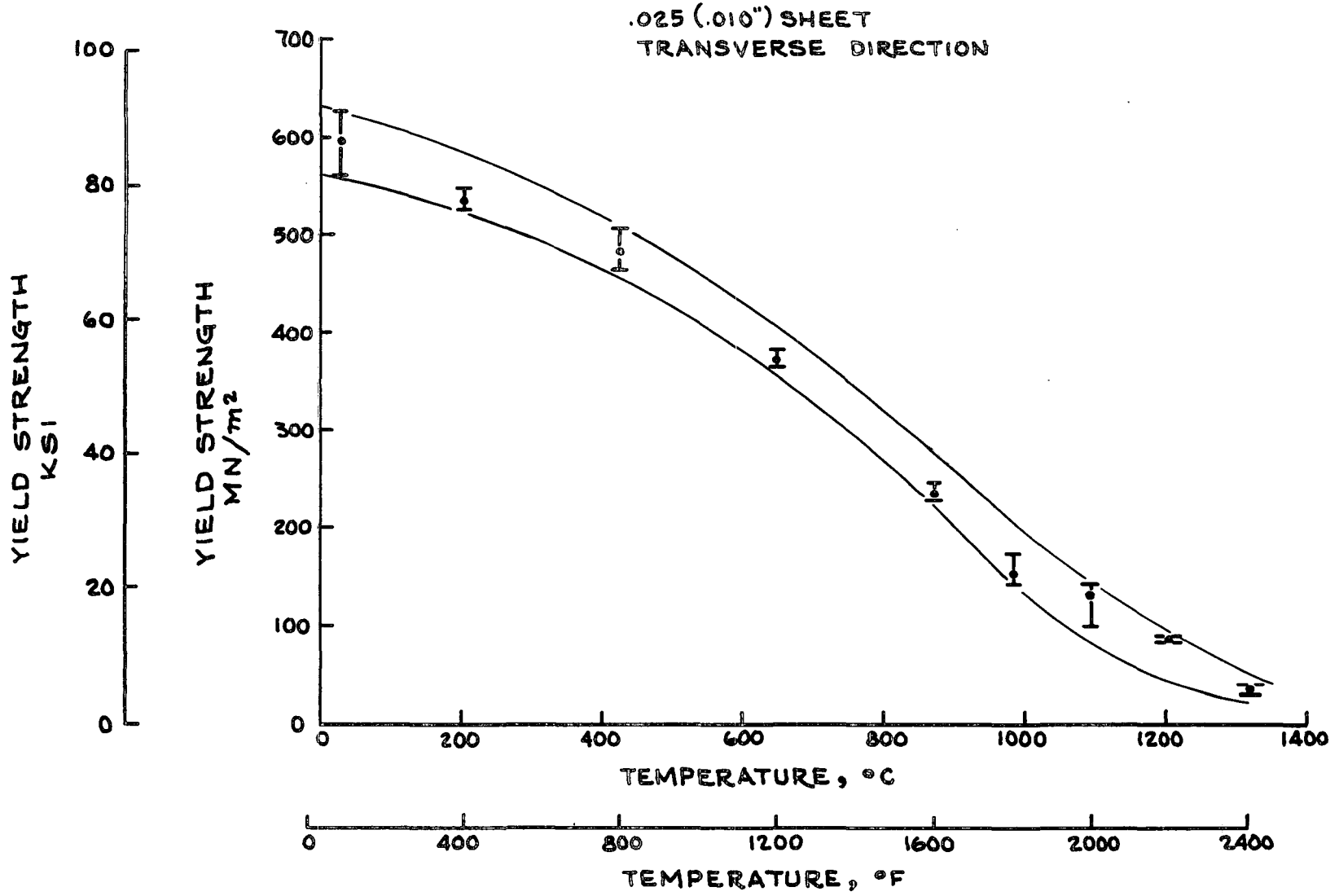


FIGURE 40. YIELD STRENGTH AS A FUNCTION OF TEMPERATURE FOR TDNiCr SHEET

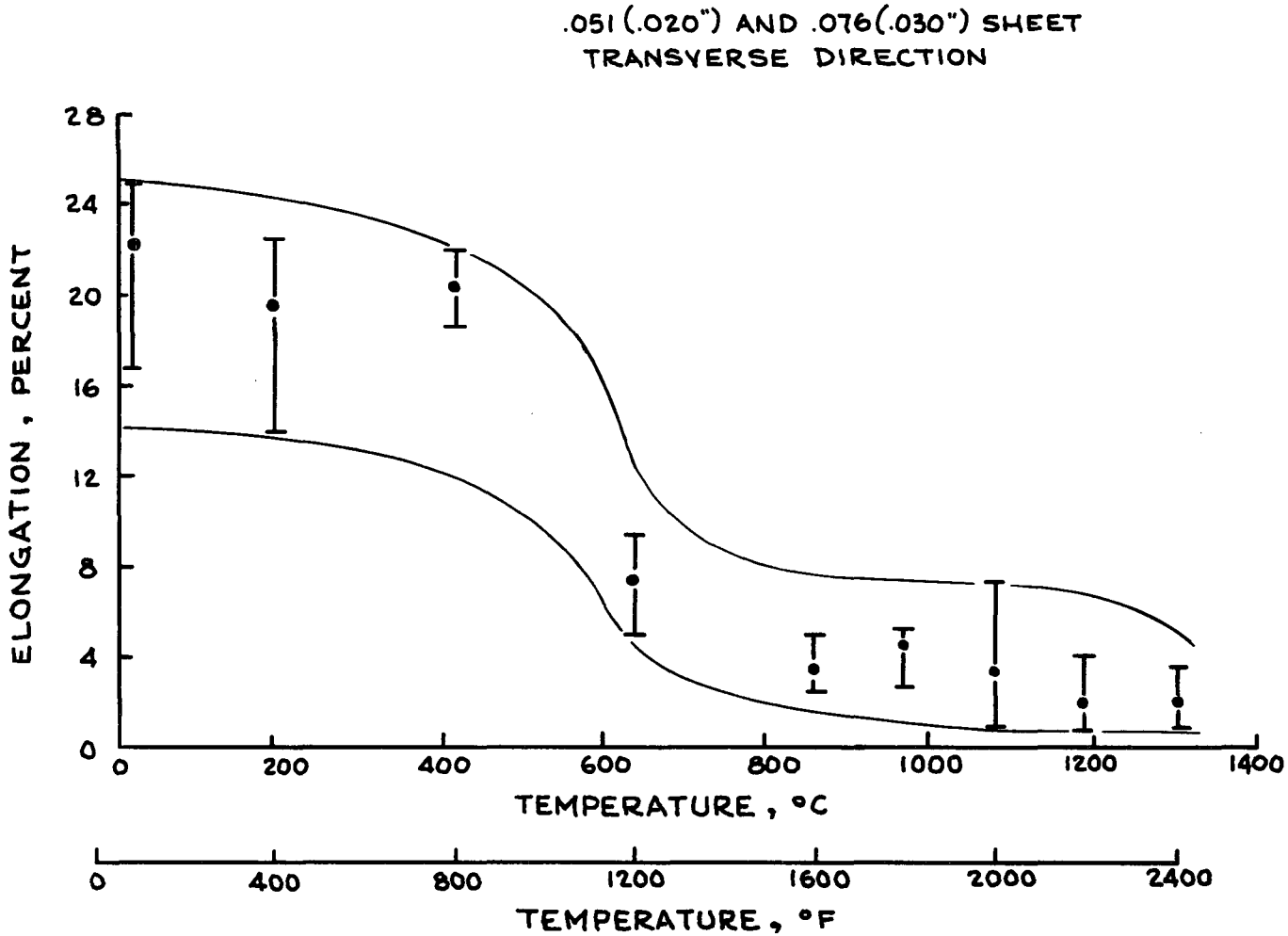


FIGURE 41. PERCENT ELONGATION AS A FUNCTION OF TEMPERATURE FOR TDNiCr SHEET

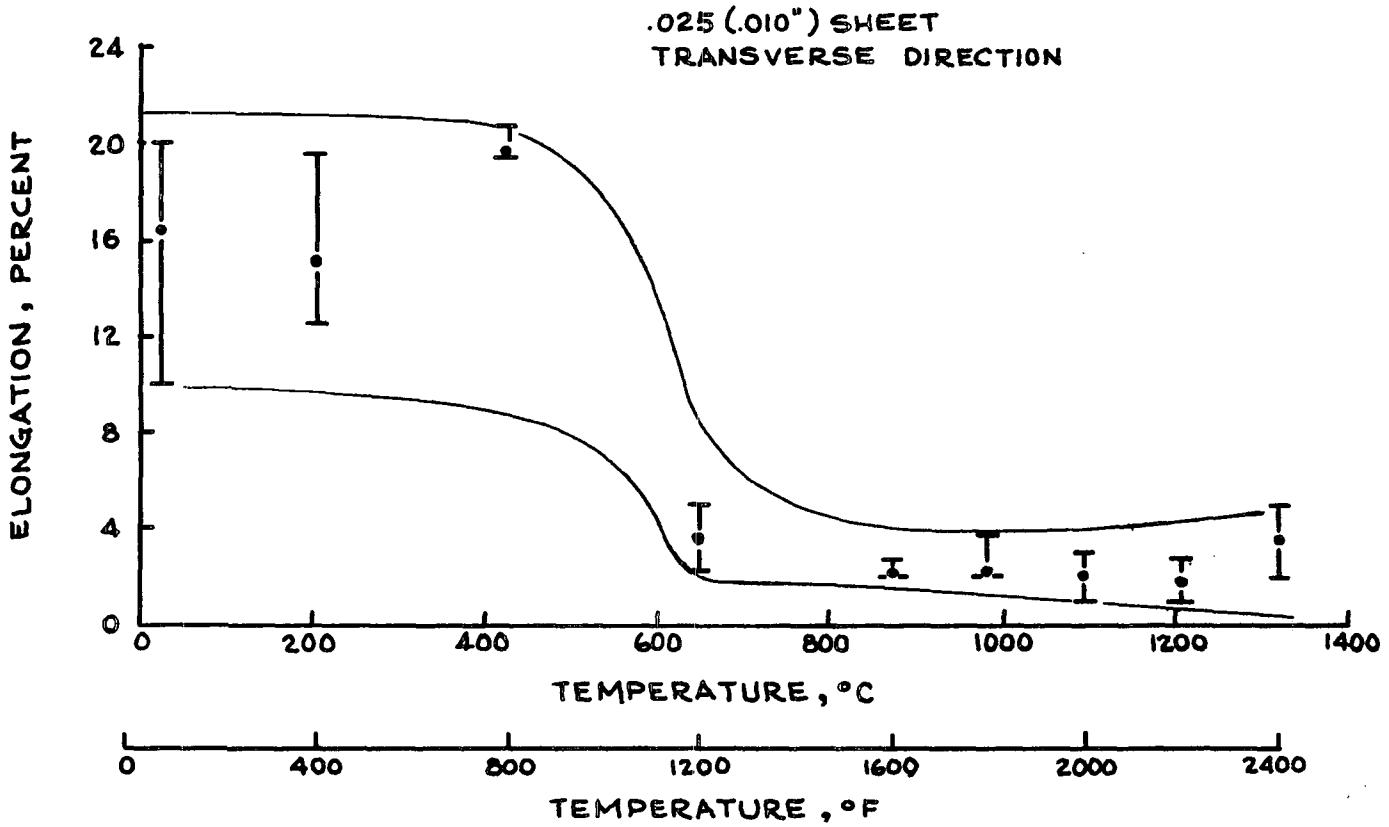


FIGURE 42. PERCENT ELONGATION AS A FUNCTION OF TEMPERATURE FOR TDNiCr SHEET

Two cases were encountered in which the 1093°C (2000°F) transverse elongation did not meet the 2.0% minimum, which was a goal specification for Part I of NAS 3-13490. They were Heat 3456 at 0.076 cm.(0.030 in.) and Heat 3415 at 0.025 cm. (0.010 in.)

Tensile tests were also conducted at 982°C, 1093°C and 1204°C(1800°F, 2000°F and 2200°F) on the 45° and longitudinal sheet directions. Data for these tests are in the following section.

(b.) Orientation with respect to rolling direction

It has been found that the attainment of pronounced crystallographic textures in TDNiCr is beneficial in producing high elevated temperature strengths. Crystallographic texture, however, usually creates some anisotropy of properties and, for this reason, temperature tensile strengths were measured in the longitudinal, 45° and transverse directions. Small differences were observed at room temperature and at elevated temperatures.

Samples utilized for this part of the reproducibility investigation were as follows:

Transverse-Room Temperature - Samples #1, 2 and 109
Transverse-982°C(1800°F) - " #11 and 12
Transverse-1093°C(2000°F) - " #13, 14 and 110
Transverse-1204°C(2200°F) - " #15 and 16

Longitudinal-Room Temperature	- Samples	#29, 30, 105 and 112
Longitudinal-982° C(1800° F)	- "	#129 and 130
Longitudinal-1093° C(2000° F)	- "	#31, 32, 106 and 113
Longitudinal-1204° C(2200° F)	- "	#131 and 132
45° - Room Temperature	- "	#35 and 36
45° - 982° C(1800° F)	- "	#114 and 115
45° - 1093° C(2000° F)	- "	#37 and 38
45° - 1204° C(2200° F)	- "	#116 and 117
Spares	- "	#33, 34, 39, 40 and 41

The results are tabulated in Table 40. All heats and all gauges have been averaged for each orientation. It is noted that at room temperature the longitudinal direction has the highest ultimate tensile strength, 886.7 MN/m^2 (128.7 ksi) and yield strength, 610.5 MN/m^2 (88.6 ksi) but the lowest percent elongation (13.6%). Transverse and 45° room temperature strengths are nearly equivalent. At elevated temperatures from 982° C to 1204° C(1800° F to 2200° F), the transverse direction is the weakest direction by a small amount, while the 45° and longitudinal directions are approximately equivalent. Also there is a slight indication that the longitudinal direction is the most ductile at elevated temperatures.

(c.) Location in Sheet

Room temperature and 1093° C(2000° F) tensile specimens were procured from various locations in one sheet of each heat and gauge to determine whether any correlation exists between tensile properties and sheet location. Such a phenomenon might be caused, for example, by small differences in rolling temperatures due to the edges or ends cooling faster than the center.

TABLE 40

TENSILE PROPERTIES OF TDNiCr SHEET
AS A FUNCTION OF SHEET ORIENTATION

Orientation	Test Temp. °C	°F	UTS* MN/m^2	ksi	YS* MN/m^2	ksi	Elong.* %
Transverse	Room	Room	845.4	122.7	583.6	84.7	20.2
45°	Room	Room	830.9	120.6	592.5	86.0	16.8
Longitudinal	Room	Room	886.7	128.7	610.5	88.6	13.6
Transverse	982	1800	164.7	23.9	163.3	23.7	3.2
45°	982	1800	170.9	24.8	168.1	24.4	3.6
Longitudinal	982	1800	177.8	25.8	173.6	25.2	4.7
Transverse	1093	2000	137.1	19.9	137.1	19.9	3.1
45°	1093	2000	145.4	21.1	144.7	21.0	3.0
Longitudinal	1093	2000	141.9	20.6	140.6	20.4	3.3
Transverse	1204	2200	91.0	13.2	91.0	13.2	2.1
45°	1204	2200	95.1	13.8	95.1	13.8	2.5
Longitudinal	1204	2200	97.9	14.2	97.9	14.1	2.5

Specimens were identified as follows:

EDGE:

Transverse - Room Temperature	- Samples	A, D, P and S
Transverse - 1093°C(2000°F)	- "	B, E, Q and T
Longitudinal-Room Temperature	- "	H, K, N, U, and AA
Longitudinal-1093°C(2000°F)	- "	I, L, O, V, Y and BB

CENTER:

Transverse - Room Temperature	- Samples	#1, 2 and 109
Transverse - 1093°C(2000°F)	- "	#13, 14 and 110
Longitudinal-Room Temperature	- "	#29, 30, 105 and 112
Longitudinal-1093°C(2000°F)	- "	#31, 32, 106 and 113
Spares	- "	#111, 107 and 108

Table 41 is a summary of the results obtained. For clarity, the samples are listed as either from the center or the edge of the sheet, where the edge is defined as that area outside a central 45.72 x 91.44 cm.(18 x 36 in.) sheet. The longitudinal and transverse directions have been grouped separately. The values were chosen from a typical sheet of each heat and gauge.

Both room temperature and elevated temperature properties are slightly lower on the average at the edge of the sheets. Room temperature ultimate and yield strengths are approximately 27.6 MN/m^2 (4 ksi) lower at the edges and 1093°C(2000°F) strengths 6.89 MN/m^2 (<1 ksi).

(d.) Heat to Heat Variations

An examination of the heat to heat variations in R.T. and 1093°C(2000°F) strengths was made. For this work,

TABLE 41

TENSILE PROPERTIES AS A FUNCTION OF LOCATION IN SHEET

Location	Test Direction	Test °C	Temp. °F	UTS* MN/m²	UTS* ksi	YS* MN/m²	YS* ksi	Elong.* %
Center	Trans.	Room	Room	845.4	122.7	583.6	84.7	20.2
Edge	Trans.	Room	Room	813.8	118.1	560.2	81.3	20.4
Center	Trans.	1093	2000	137.8	20.0	137.8	20.0	3.2
Edge	Trans.	1093	2000	131.6	19.1	131.6	19.1	2.2
Center	Long.	Room	Room	886.7	128.7	610.5	88.6	13.6
Edge	Long.	Room	Room	864.7	125.5	587.0	85.2	14.8
Center	Long.	1093	2000	141.9	20.6	137.9	20.3	3.4
Edge	Long.	1093	2000	137.1	19.9	135.0	19.6	2.7

* Values are averages of all heats and gauges.

the following samples, which were taken from one 45.72 x 91.44 cm. (18 x 36 in.) sheet of each gauge within a heat, were averaged.

Transverse - Room Temperature - 1, 2 and 109

Transverse - 1093°C(2000°F) - 13, 14 and 110

Longitudinal-Room Temperature - 29, 30, 105 and 112

Longitudinal-1093°C(2000°F) - 31, 32, 106 and 113

The results of this study are shown in Table 42. Room temperature transverse tests for the three heats have a maximum difference of 35.1 MN/m^2(5.1 ksi) in ultimate strength, 6.2 MN/m^2(0.9 ksi) in yield strength, and 1.0% in elongation. At 1093°C(2000°F), the difference between the minimum and maximum average ultimate strength in the transverse direction was only 1.4 MN/m^2(0.2 ksi). Average percent elongations ran from 2.5% to 3.8%.

(e.) Gauge to Gauge Variations

Average tensile strengths were calculated for the longitudinal and transverse directions of all heats at each gauge. Averages were obtained from the samples listed in the previous section. The results are presented in Figures 43 to 52 inclusive. Also included are the maximum and minimum values obtained in the testing.

Strengths at 1093°C(2000°F) were slightly lower for 0.025 cm.(0.010 in.) sheet. Also, total data spread at this gauge was larger than for the heavier gauges of sheet. At room temperature, 0.025 cm.(0.010 in.) sheet again behaved differently, having significantly lower ultimate tensile strengths and percent

C 3

TABLE 42

HEAT TO HEAT STRENGTH VARIATIONS FOR TDNiCr SHEET

Heat No.	Test °C	Temp. °F	Orientation	UTS* MN/m^2	UTS* ksi	YS* MN/m^2	YS* ksi	Elong. * %
3415	Room	Room	Trans.	830.3	120.5	580.8	84.3	19.9
3415	Room	Room	Long.	867.5	125.9	604.3	87.7	14.0
3456	Room	Room	Trans.	865.4	125.6	588.4	85.4	19.9
3456	Room	Room	Long.	910.2	132.1	619.4	89.9	13.7
3502	Room	Room	Trans.	848.2	123.1	580.8	84.3	20.9
3502	Room	Room	Long.	881.9	128.0	608.4	88.3	13.1
3415	1093	2000	Trans.	137.1	19.9	136.4	19.8	3.2
3415	1093	2000	Long.	138.5	20.1	137.8	20.0	3.5
3456	1093	2000	Trans.	137.8	20.0	137.8	20.0	2.5
3456	1093	2000	Long.	146.1	21.2	144.0	20.9	2.8
3502	1093	2000	Trans.	138.5	20.1	138.5	20.1	3.8
3502	1093	2000	Long.	139.9	20.3	137.8	20.0	3.8

* Values presented are averages of all gauges within each heat.

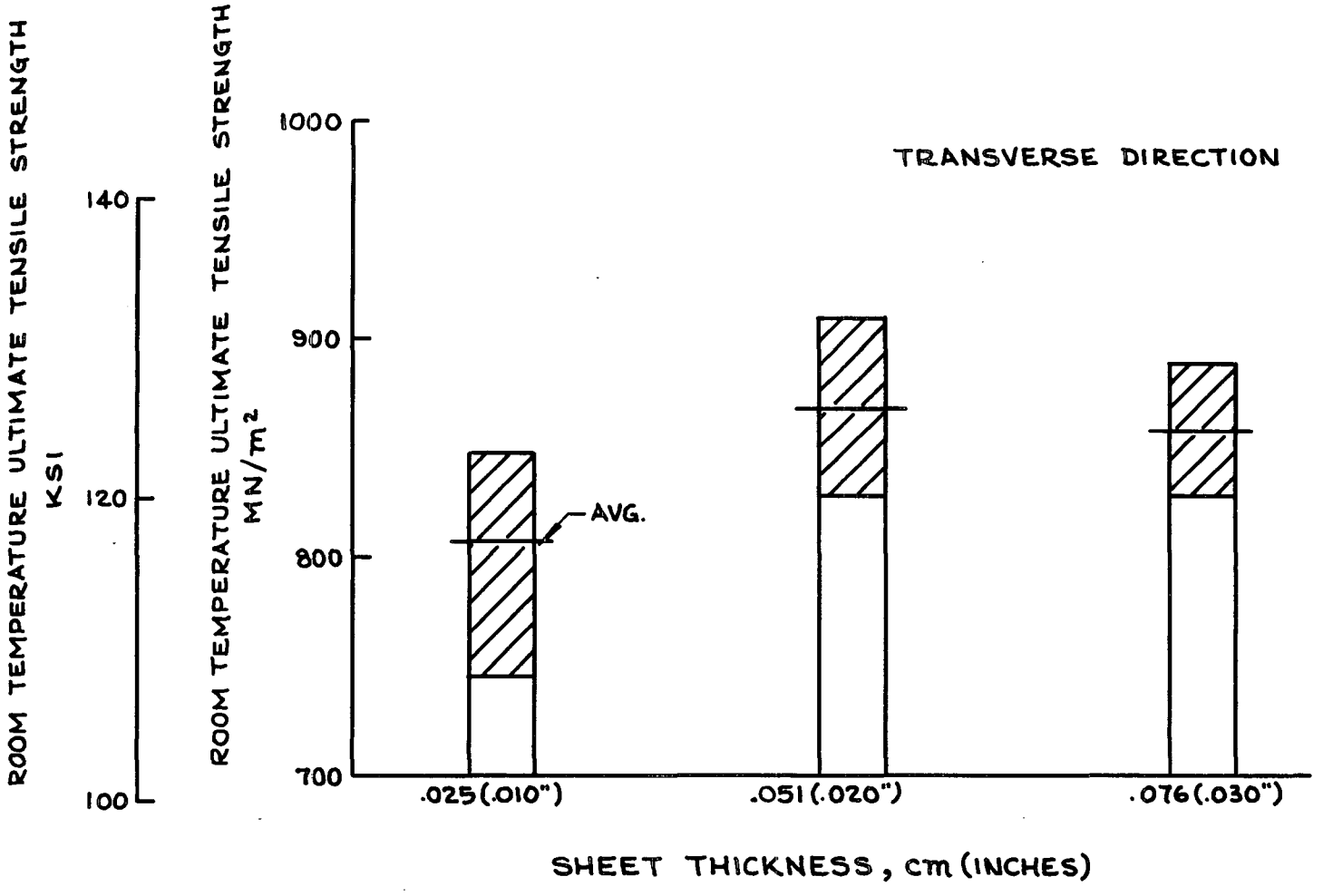


FIGURE 43. ROOM TEMPERATURE ULTIMATE TENSILE STRENGTH AS A FUNCTION OF GAUGE

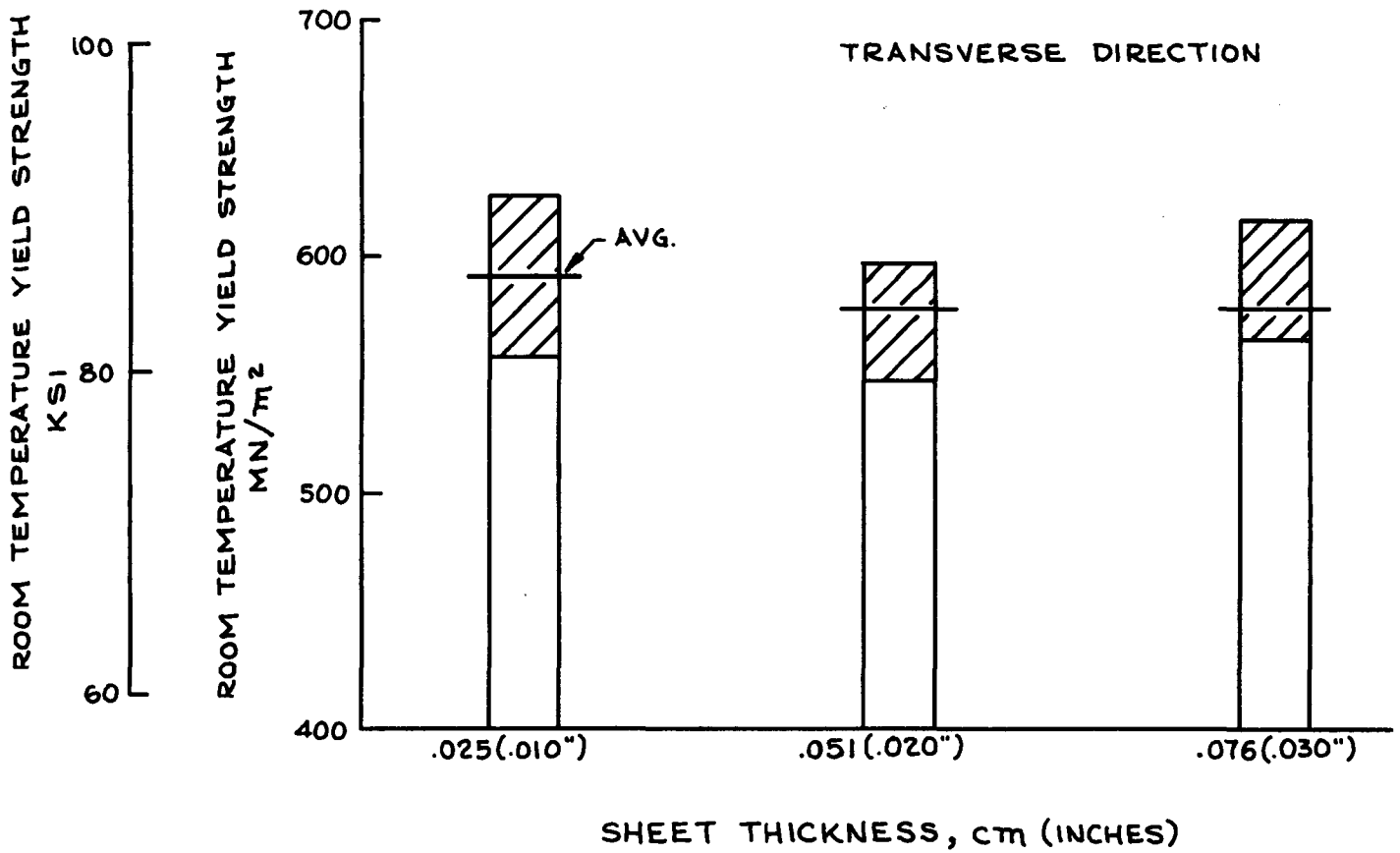


FIGURE 44. ROOM TEMPERATURE YIELD STRENGTH AS A FUNCTION OF GAUGE

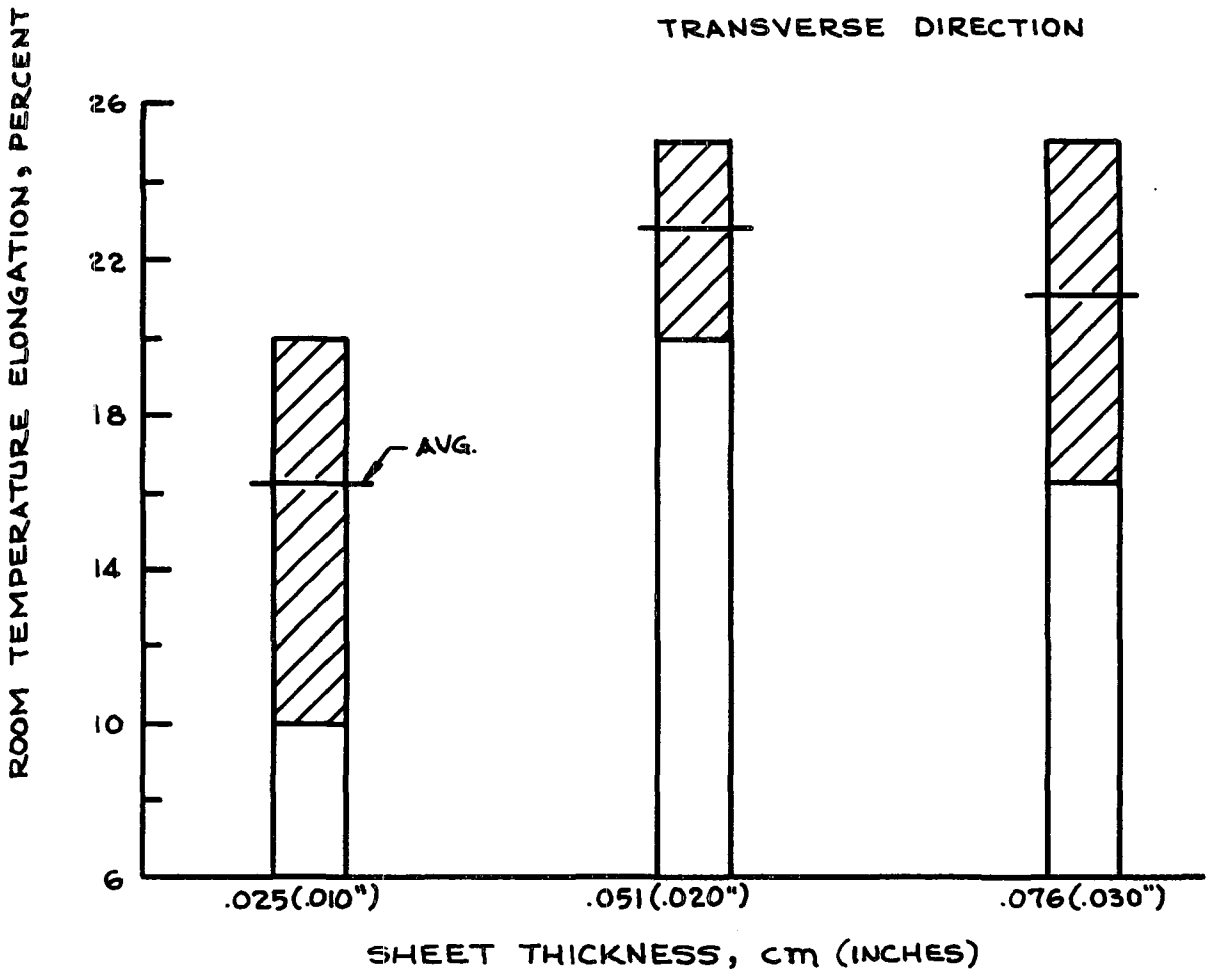


FIGURE 45. ROOM TEMPERATURE ELONGATIONS AS A FUNCTION OF GAUGE

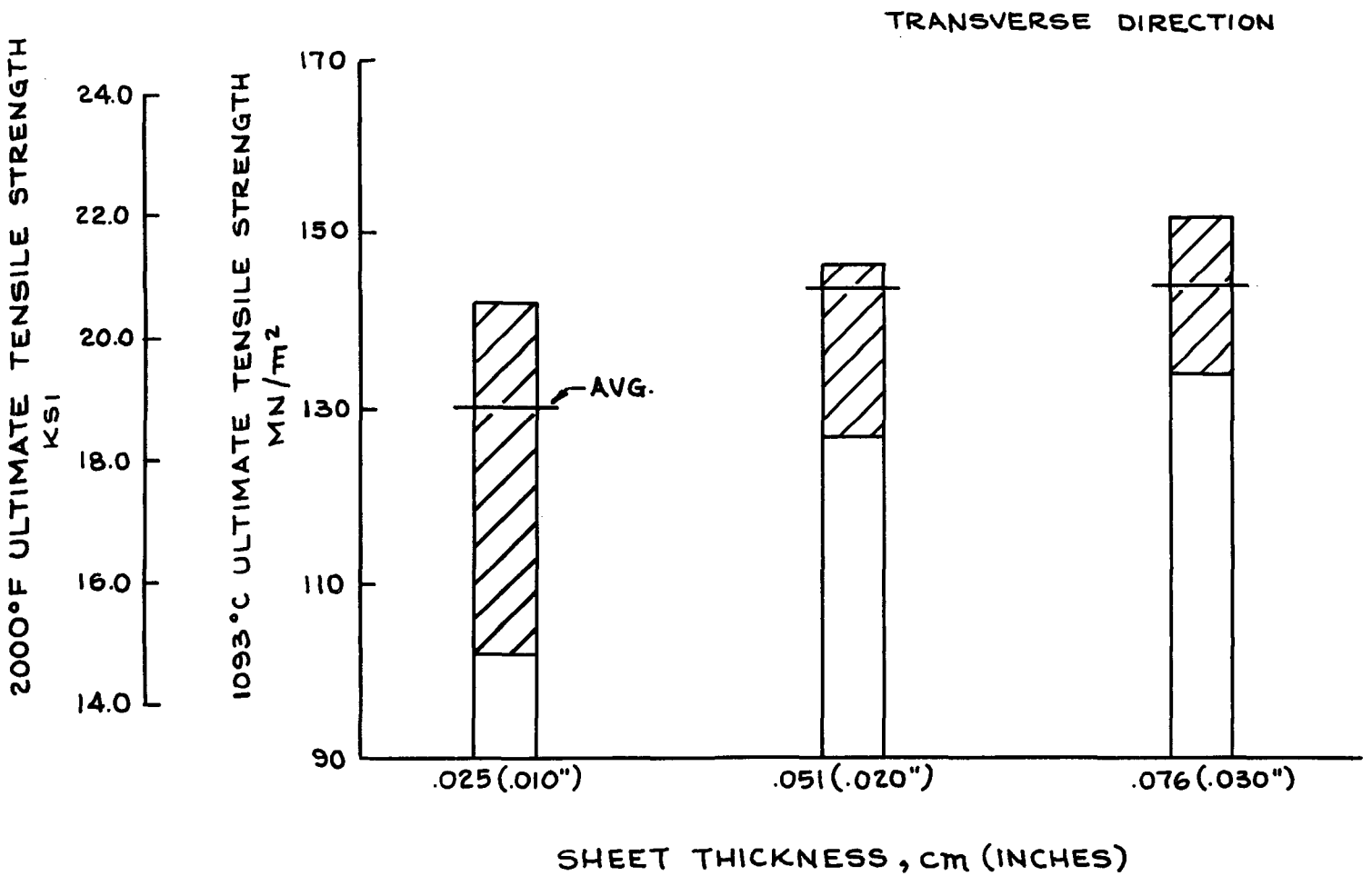


FIGURE 46. 1093°C(2000°F) ULTIMATE TENSILE STRENGTH AS A FUNCTION OF GAUGE

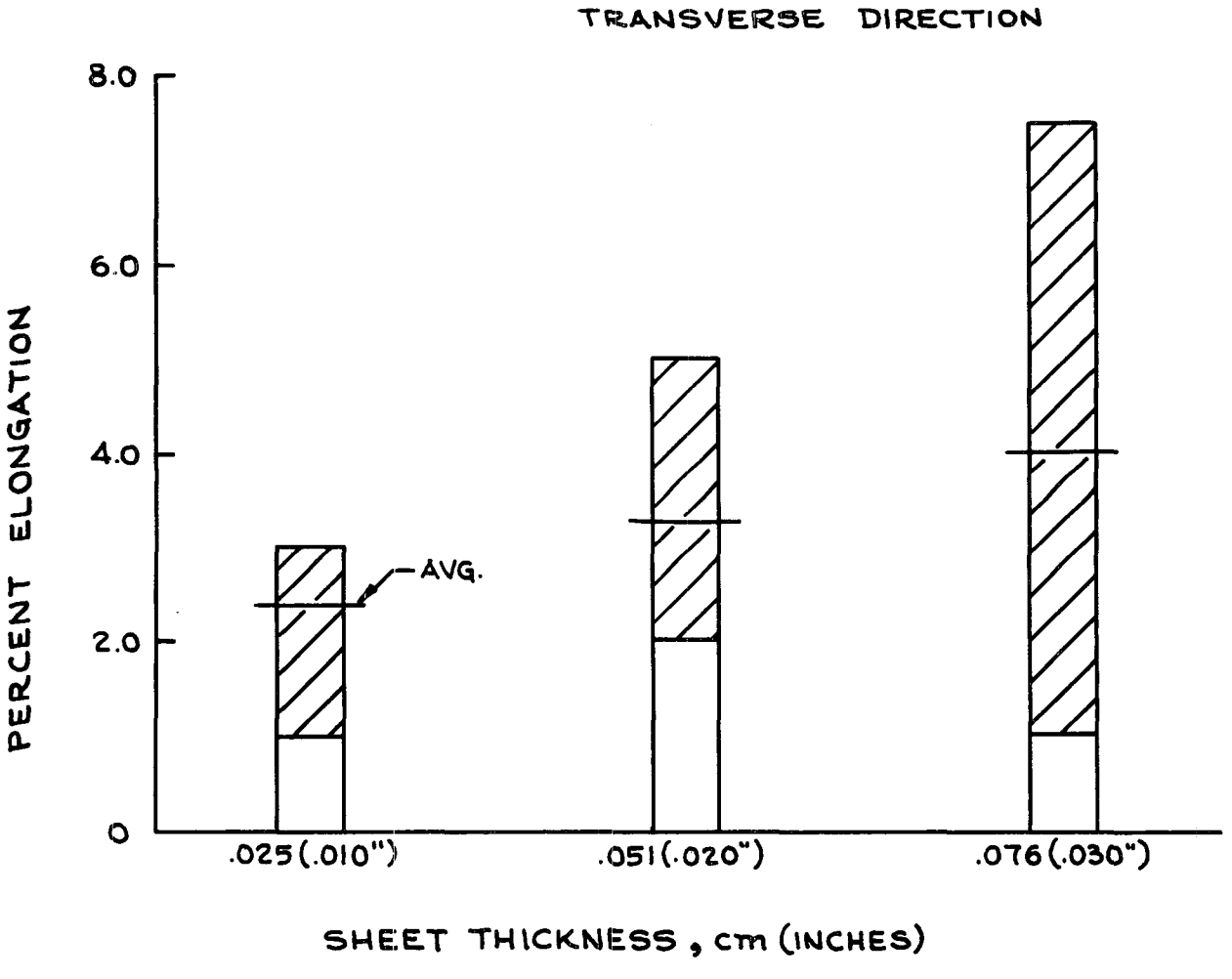


FIGURE 47. 1093°(2000°F) ELONGATION AS A FUNCTION OF GAUGE

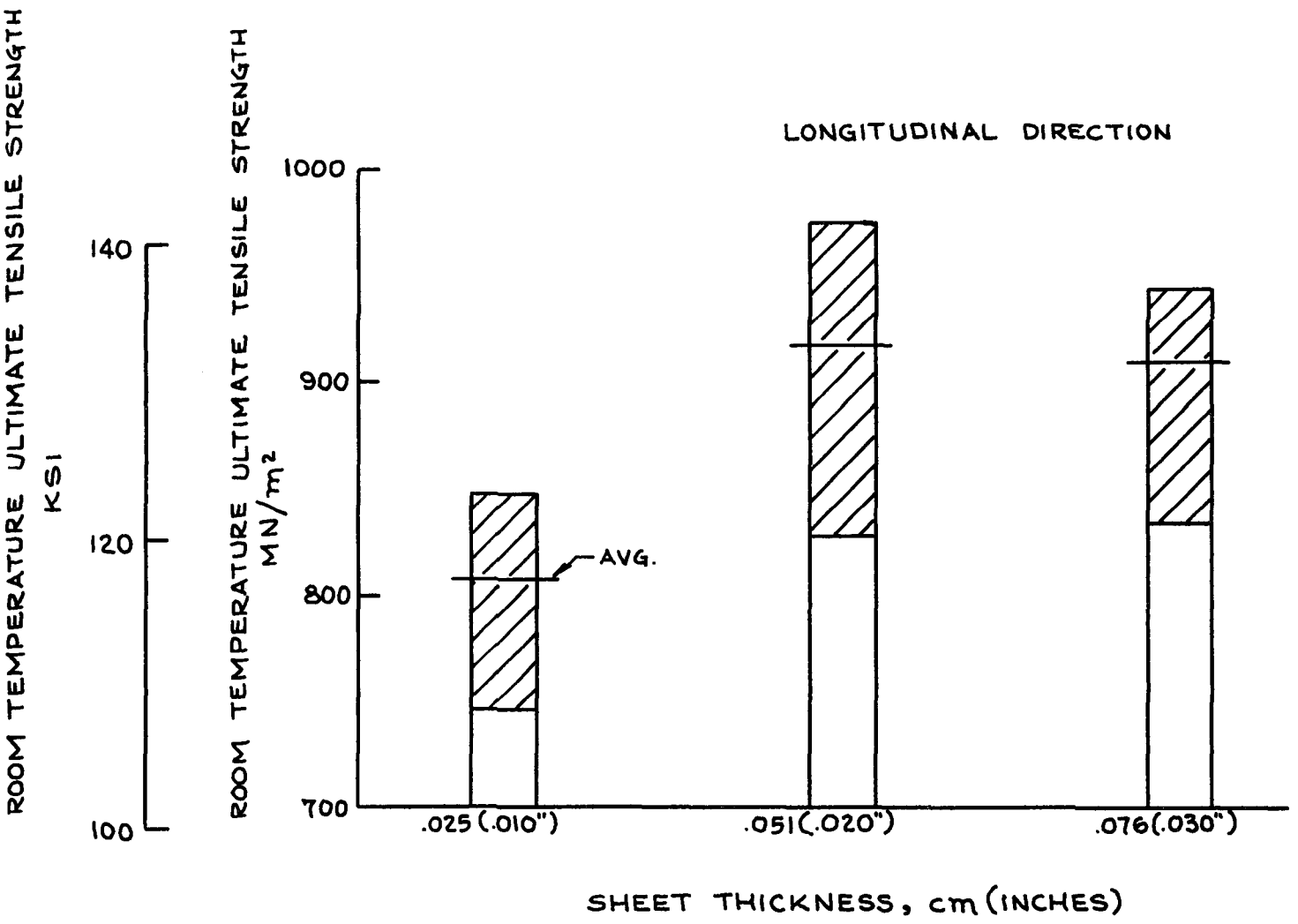


FIGURE 48. ROOM TEMPERATURE ULTIMATE TENSILE STRENGTH AS A FUNCTION OF GAUGE

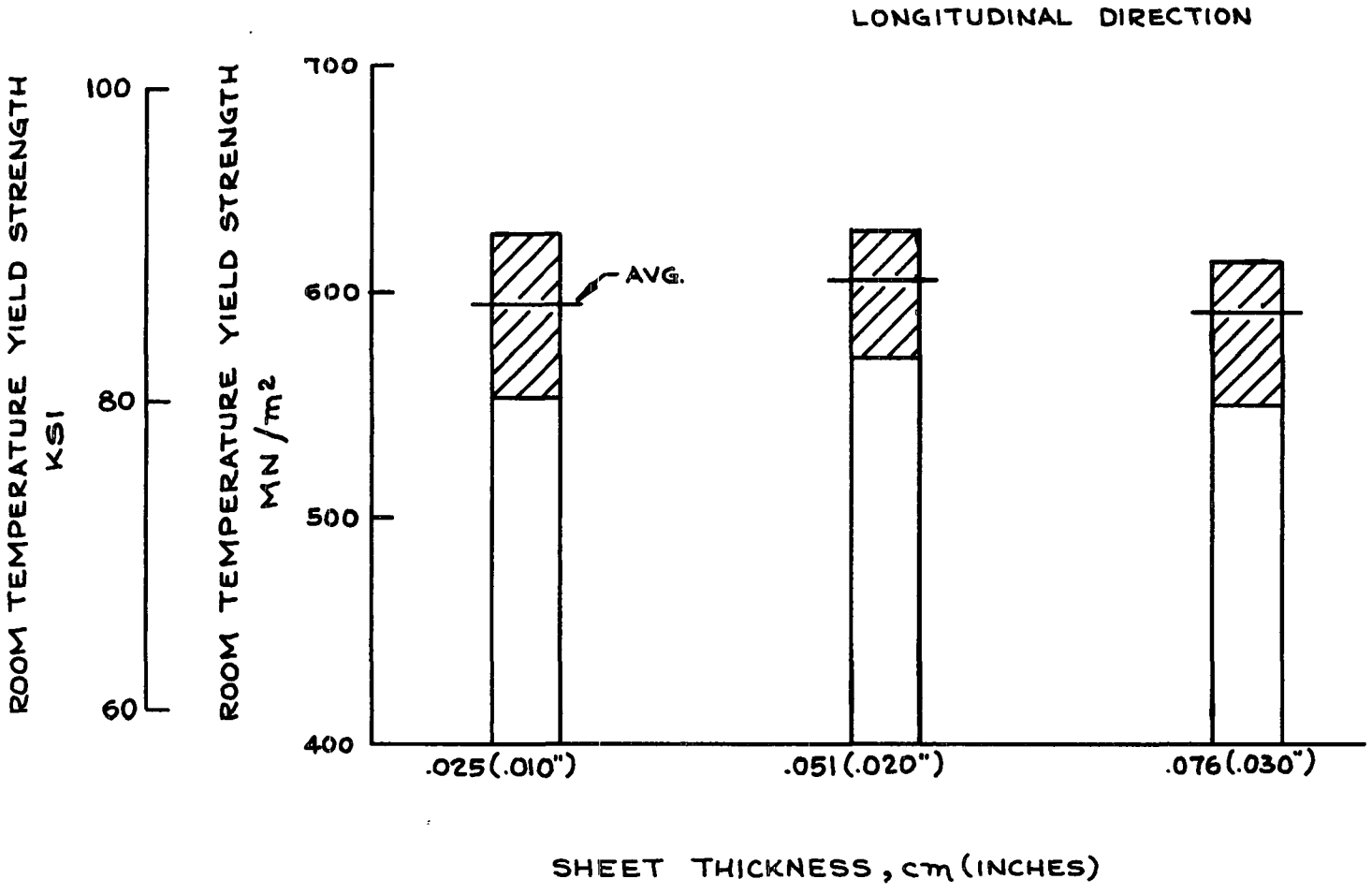


FIGURE 49. ROOM TEMPERATURE YIELD STRENGTH AS A FUNCTION OF GAUGE

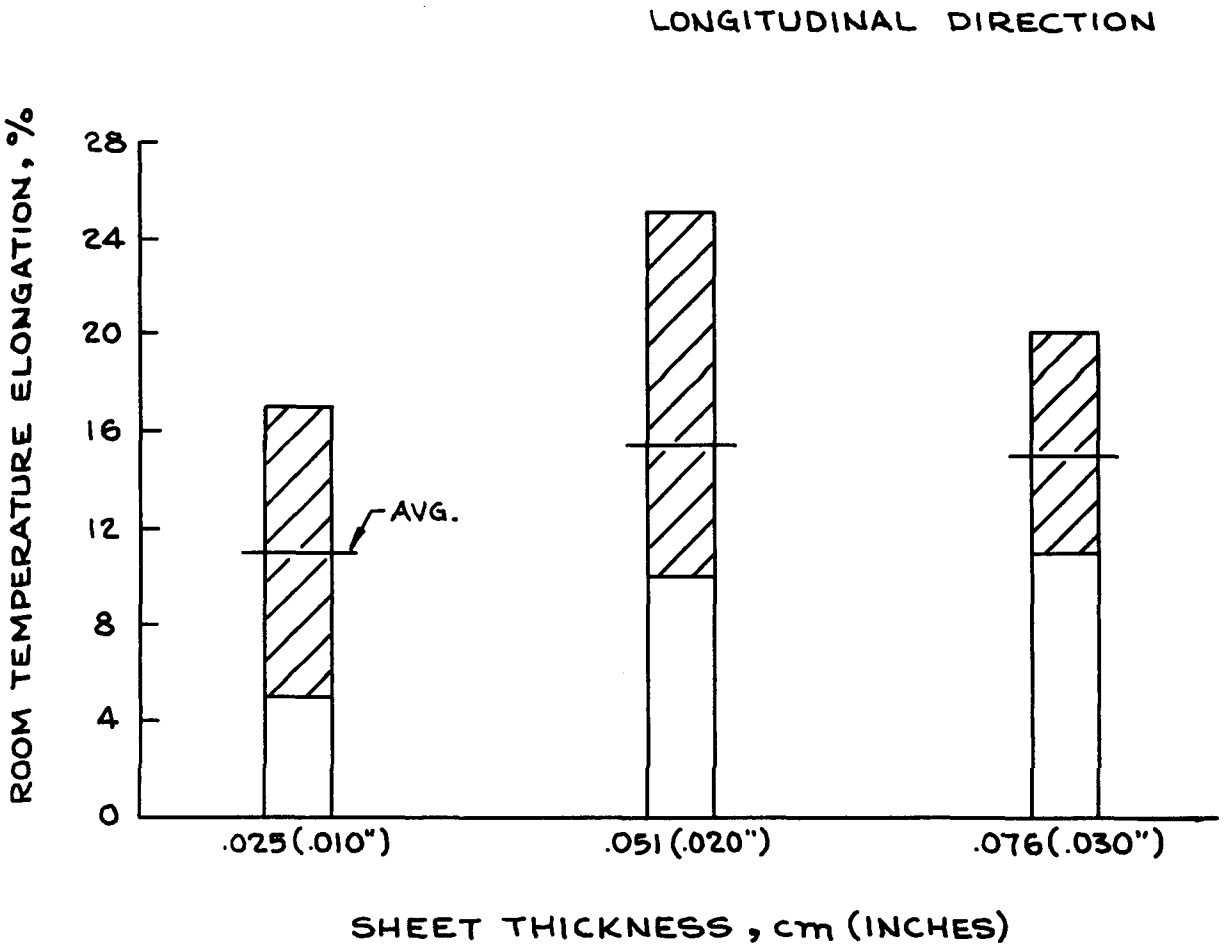


FIGURE 50. ROOM TEMPERATURE ELONGATION AS A FUNCTION OF GAUGE

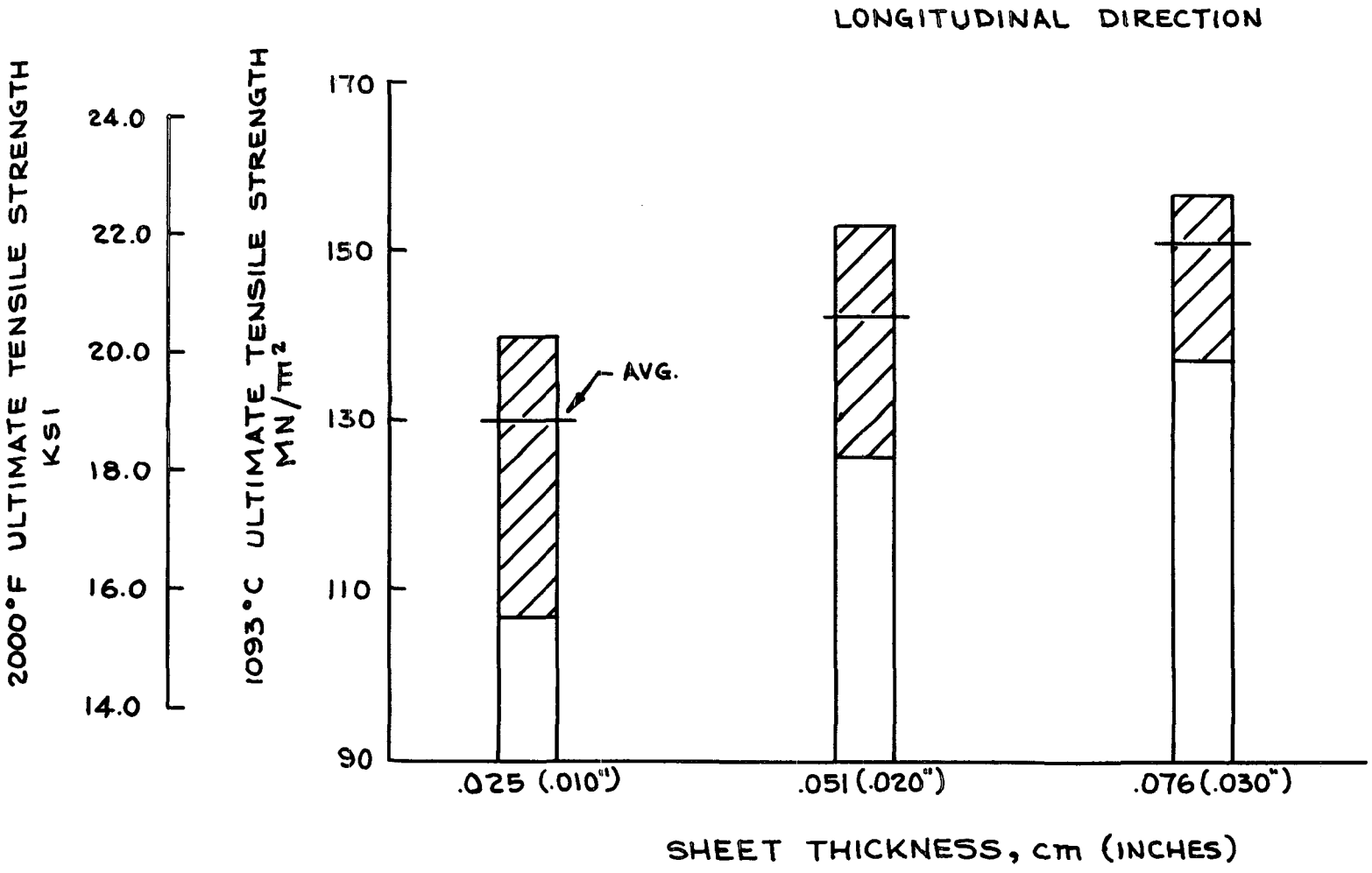


FIGURE 51. 1093°C(2000°F) ULTIMATE TENSILE STRENGTH AS A FUNCTION OF GAUGE

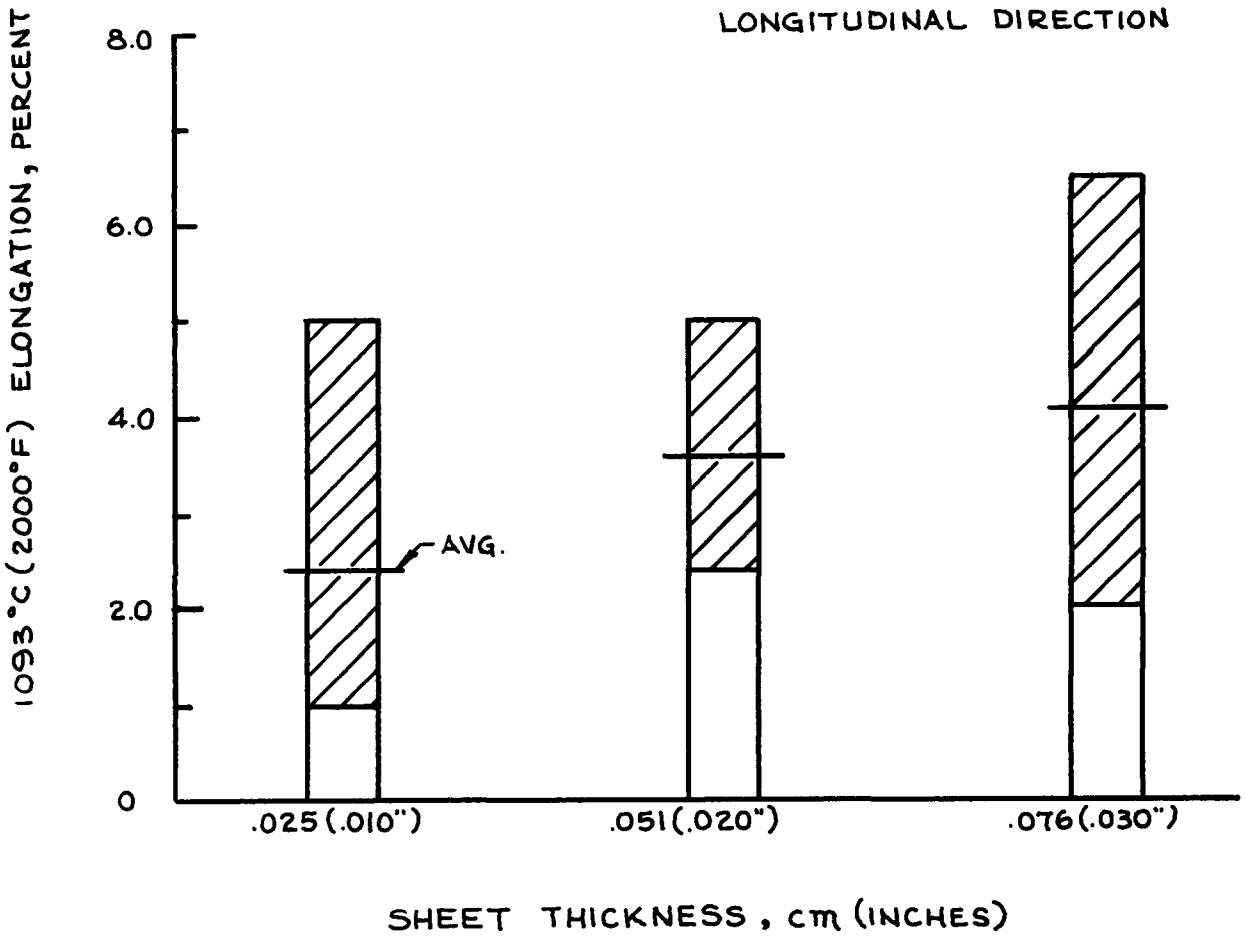


FIGURE 52. 1093°C (2000°F) PERCENT ELONGATION AS A FUNCTION OF GAUGE

elongations. The yield strengths, however, were significantly higher, due probably to the 5% cold finishing pass which is now part of the standard process for this gauge.

Fansteel recognized the phenomenon of lower strength values for material of less than 0.051 cm.(0.020 in.) thickness and had adjusted the TDNiCr specification for 0.025 to 0.048 cm. (0.010 to 0.019 in.) sheet.

(f.) Sheet to Sheet Variation

Results of tensile tests on offal material were used to compare sheet to sheet variations within a given heat and gauge. The tensile specimens used were:

Transverse - Room Temperature - Samples A, D, P and S
Transverse - 1093°C(2000°F) - " B, E, Q and T
Longitudinal-Room Temperature - " H, K, N, U and AA
Longitudinal-1093°C(2000°F) - " I, L, O, V, Y and BB

Tables 43 and 44 are tabulations of average ultimate tensile strengths and percent elongation for two sheets from each heat and gauge. Both the longitudinal and transverse directions are compared at room temperature and 1093°C(2000°F). Tables 45 and 46 present differences from sheet to sheet.

Testing was limited to offal material because only one sheet per heat/gauge was sectioned as in Figure 31.

Room temperature variations range from 3.4 to 110.9 MN/m^2 (0.5 to 16.1 ksi) for the ultimate tensile strength. Yield strength variations are proportionately lower. The maximum

TABLE 43

ROOM TEMPERATURE PROPERTIES FOR EACH TDNiCr SHEET

Heat No.	Gauge cm.	Gauge in.	Sheet No.	Direction	Avg. FTU MN/m^2	Avg. FTU ksi	Avg. FTY MN/m^2	Avg. FTY ksi	Avg. Elong. %
3415	0.076	0.030	11	Trans.	806.1	117.0	545.0	79.1	19.4
3415	0.076	0.030	12	Trans.	811.6	117.8	548.8	79.8	20.6
3415	0.076	0.030	11	Long.	866.1	125.7	562.9	81.7	17.7
3415	0.076	0.030	12	Long.	867.6	125.2	556.7	80.8	17.8
3415	0.051	0.020	13	Trans.	776.5	112.7	510.5	74.1	24.6
3415	0.051	0.020	14	Trans.	825.4	119.8	556.0	80.7	21.9
3415	0.051	0.020	13	Long.	814.4	118.2	534.7	77.6	15.2
3415	0.051	0.020	14	Long.	895.0	129.9	593.2	86.1	18.2
3415	0.025	0.010	16	Trans.	788.2	114.4	592.5	86.0	16.5
3415	0.025	0.010	17	Trans.	816.5	118.5	642.1	93.2	13.3
3415	0.025	0.010	16	Long.	777.2	112.8	659.4	95.7	5.6
3415	0.025	0.010	17	Long.	817.8	118.7	664.2	96.4	9.7
3456	0.076	0.030	9	Trans.	813.7	118.1	526.4	76.4	21.4
3456	0.076	0.030	10	Trans.	826.1	119.9	532.6	77.3	22.2
3456	0.076	0.030	9	Long.	893.6	129.7	567.7	82.4	18.8
3456	0.076	0.030	10	Long.	908.8	131.9	567.0	82.3	19.1
3456	0.051	0.020	6	Trans.	848.2	123.1	568.4	82.5	22.1
3456	0.051	0.020	7	Trans.	815.1	118.3	556.7	80.8	22.7
3456	0.051	0.020	6	Long.	920.5	133.6	604.3	87.7	17.7
3456	0.051	0.020	7	Long.	870.2	126.3	563.6	81.8	17.7
3456	0.025	0.010	18	Trans.	840.6	122.0	623.5	90.5	14.2
3456	0.025	0.010	19	Trans.	810.3	117.6	585.7	85.0	18.7
3456	0.025	0.010	18	Long.	811.0	117.7	629.7	91.4	6.5
3456	0.025	0.010	19	Long.	804.1	116.7	586.3	85.1	5.4
3502	0.076	0.030	4	Trans.	857.8	124.5	553.2	80.3	22.4
3502	0.076	0.030	5	Trans.	863.3	125.3	569.8	82.7	21.0
3502	0.076	0.030	4	Long.	899.8	130.6	572.6	83.1	16.8
3502	0.076	0.030	5	Long.	920.5	133.6	585.0	84.9	17.4
3502	0.051	0.020	1	Trans.	784.8	113.9	532.6	77.3	21.8
3502	0.051	0.020	2	Trans.	872.3	126.6	582.2	84.5	21.4
3502	0.051	0.020	1	Long.	858.5	124.6	569.8	82.7	16.6
3502	0.051	0.020	2	Long.	970.1	140.8	658.0	95.5	18.2
3502	0.025	0.010	20	Trans.	806.8	117.1	571.9	83.0	16.4
3502	0.025	0.010	24	Trans.	878.5	127.5	621.5	90.2	21.5
3502	0.025	0.010	20	Long.	868.8	126.1	604.9	87.8	14.0
3502	0.025	0.010	24	Long.	961.8	139.6	633.2	91.9	13.3

TABLE 44

1093°C(2000°F) TENSILE PROPERTIES FOR EACH TDNiCr SHEET

Heat No.	Gauge cm.	Gauge in.	Sheet No.	Direction	UTS MN/m^2	UTS ksi	YS MN/m^2	YS ksi	Elong. %
3456	0.025	0.010	19	Trans.	139.2	20.2	139.2	20.2	2.4
				Long.	129.5	18.8	129.5	18.8	2.6
3456	0.025	0.010	18	Trans.	128.8	18.7	128.8	18.7	2.0
				Long.	129.5	18.8	129.5	18.8	2.3
3456	0.051	0.020	6	Trans.	121.3	17.6	121.3	17.6	1.5
				Long.	139.9	20.3	136.4	19.8	2.2
3456	0.051	0.020	7	Trans.	137.8	20.0	137.8	20.0	3.0
				Long.	145.4	21.1	144.0	20.9	2.6
3456	0.076	0.030	9	Trans.	127.5	18.5	127.5	18.5	2.3
				Long.	141.9	20.6	137.2	20.2	2.8
3456	0.076	0.030	10	Trans.	137.8	20.0	137.8	20.0	2.0
				Long.	147.4	21.4	145.4	21.1	2.9
3502	0.025	0.010	20	Trans.	126.1	18.3	126.1	18.3	2.6
				Long.	133.0	19.3	133.0	19.3	2.6
3502	0.025	0.010	24	Trans.	117.8	17.1	117.8	17.1	2.8
				Long.	124.0	18.0	123.3	17.9	3.2
3502	0.051	0.020	1	Trans.	136.4	19.8	136.4	19.8	3.4
				Long.	139.9	20.3	137.1	19.9	3.6
3502	0.051	0.020	2	Trans.	127.5	18.5	127.5	18.5	1.4
				Long.	135.1	19.6	133.0	19.3	2.2
3502	0.076	0.030	4	Trans.	129.5	18.8	129.5	18.8	1.7
				Long.	141.9	20.6	140.6	20.4	2.3
3502	0.051	0.020	5	Trans.	137.1	19.9	136.4	19.8	2.7
				Long.	145.4	21.1	142.6	20.7	3.4
3415	0.025	0.010	16	Trans.	127.5	18.5	127.5	18.5	2.9
				Long.	133.1	19.6	133.7	19.4	4.0
3415	0.025	0.010	17	Trans.	128.5	18.7	128.5	18.7	2.9
				Long.	133.7	19.4	130.2	18.9	3.6
3415	0.051	0.020	13	Trans.	121.3	17.6	121.3	17.6	2.0
				Long.	123.3	17.9	119.9	17.4	2.1
3415	0.051	0.020	14	Trans.	134.4	19.5	133.7	19.4	2.0
				Long.	141.9	20.6	138.5	20.1	2.9
3415	0.076	0.030	11	Trans.	131.6	19.1	130.2	18.9	3.9
				Long.	137.1	19.9	135.7	19.7	3.4
3415	0.076	0.030	12	Trans.	126.8	18.4	126.1	18.3	2.0
				Long.	136.4	19.8	135.7	19.7	2.6

TABLE 45

DIFFERENCE IN AVERAGE ROOM TEMPERATURE
TENSILE PROPERTIES FOR SHEETS WITHIN A SINGLE HEAT & GAUGE

Heat No.	Gauge cm.	Gauge in.	Direction	Δ UTS MN/m^2	Δ UTS ksi	Δ YS MN/m^2	Δ YS ksi	Δ Elong.%
3415	0.076	0.030	Trans.	5.5	.8	4.8	.7	1.2
3415	0.076	0.030	Long.	3.4	.5	4.8	.7	.1
3415	0.051	0.020	Trans.	48.9	7.1	45.4	6.6	2.7
3415	0.051	0.020	Long.	80.6	11.7	58.5	8.5	3.0
3415	0.025	0.010	Trans.	28.2	4.1	49.5	7.2	3.2
3415	0.025	0.010	Long.	54.4	7.9	4.8	.7	4.1
3456	0.076	0.030	Trans.	12.4	1.8	6.2	.9	.8
3456	0.076	0.030	Long.	15.2	2.2	.7	.1	.3
3456	0.051	0.020	Trans.	33.1	4.8	11.7	1.7	.6
3456	0.051	0.020	Long.	50.3	7.3	40.7	5.9	0
3456	0.025	0.010	Trans.	30.3	4.4	37.9	5.5	4.5
3456	0.025	0.010	Long.	6.9	1.0	43.4	6.3	1.1
3502	0.076	0.030	Trans.	5.5	.8	16.5	2.4	1.4
3502	0.076	0.030	Long.	20.7	3.0	12.4	1.8	.6
3502	0.051	0.020	Trans.	87.5	12.7	49.6	7.2	.4
3502	0.051	0.020	Long.	111.0	16.1	88.2	12.8	1.6
3502	0.025	0.010	Trans.	71.7	10.4	49.6	7.2	5.1
3502	0.025	0.010	Long.	93.0	13.5	28.2	4.1	.7

TABLE 46

DIFFERENCES IN AVERAGE 1093°C(2000°F) TENSILE PROPERTIES FOR SHEETS WITHIN A SINGLE HEAT AND GAUGE

Heat No.	Gauge cm.	Gauge in.	Direction	Δ UTS MN/m^2	Δ UTS ksi	Δ YS MN/m^2	Δ YS ksi	Δ Elong.%
3456	0.025	0.010	Trans.	10.3	1.5	10.3	1.5	.4
			Long.	0.0	0.0	0.0	0.0	.3
	0.051	0.020	Trans.	16.5	2.4	16.5	2.4	.5
			Long.	5.5	.8	7.6	1.1	.4
	0.076	0.030	Trans.	10.3	1.5	10.3	1.5	.3
			Long.	5.5	.8	6.2	.9	.1
3502	0.025	0.010	Trans.	8.3	1.2	8.3	1.2	.2
			Long.	9.0	1.3	9.7	1.4	.6
	0.051	0.020	Trans.	8.0	1.3	9.0	1.3	2.0
			Long.	4.8	.7	4.7	.6	1.4
	0.076	0.030	Trans.	7.6	1.1	6.9	1.0	1.0
			Long.	6.9	1.0	7.6	1.1	.1
3415	0.025	0.010	Trans.	1.4	.2	1.4	.2	.0
			Long.	1.4	.2	3.4	.5	.4
	0.051	0.020	Trans.	13.1	1.9	12.4	1.8	.0
			Long.	18.6	2.7	18.6	2.7	.8
	0.076	0.030	Trans.	4.8	.7	4.1	.6	1.9
			Long.	.7	.1	0.0	.0	1.2

difference in ultimate tensile strength at 1093°C(2000°F) was 18.6 MN/m^2(2.7 ksi), while the average difference was only 7.6 MN/m^2(1.1 ksi). Similar values for percent elongation were 2.0% and o.64% respectively.

(g.) Statistical Analysis

The 1093°C(2000°F) transverse ultimate tensile strength data were utilized for calculations of the means, standard deviations, 95% and 99.7% probability bands for all three gauges of sheet material. Test results from all sheets were utilized to maximize the number of data points. The number of samples was 67 for 0.051 cm. and 0.076 cm. (0.020 and 0.030 in.), and 35 for 0.025 cm.(0.010 in.) sheet respectively.

Calculations were made assuming that the data follow a normal distribution. The results were:

0.051 and 0.076 cm.(0.020 and 0.030 in.) Sheet:

$\overline{UTS}$ = 129.5 MN/m^2(18.79 ksi)

where $\overline{UTS}$ is the mean ultimate tensile strength

Std. Deviation = σ = 8.6 MN/m^2(1.25 ksi)

95% probability band ($\overline{UTS} \pm 2\sigma$):

112.2 to 146.7 MN/m^2 (16.29 to 21.29 ksi)

99.7% probability band ($\overline{UTS} \pm 3\sigma$):

103.6 to 155.3 MN/m^2 (15.04 to 22.54 ksi)

0.025 cm.(0.010 in.) Sheet

UTS = 125.4 MN/m^2(18.20 ksi)

σ = 12.7 MN/m^2(1.85 ksi)

95% probability band:

99.9 to 150.9 MN/m^2(14.50 to 21.90 ksi)

99.7% probability band:

87.2 to 163.6 MN/m^2(12.65 to 23.75 ksi)

(2.) Stress Rupture

Stress rupture tests were conducted on the reproducibility series of heats and gauges to determine the stress to produce a 100 hour life at 982°C, 1093°C and 1204°C (1800°F, 2000°F and 2200°F). Testing was performed on transverse specimens only. Each of the heats and gauges exceeded the Fansteel Specification of 20 hrs. life at 37.9 MN/m^2(5500 psi) and 1093°C (2000°F) for 0.051/0.076 cm. (0.020/0.030 in.) sheet and 31.1 MN/m^2 (4500 psi) for 0.025 cm.(0.010 in.) sheet.

The 982°C(1800°F) and 1093°C(2000°F) testing was performed at Fansteel. Because only one furnace at Fansteel is capable of a 1204°C(2200°F) operating temperature, these tests were conducted by Metcut Research Associates, Cincinnati, Ohio.

Tests at Fansteel were performed on Arcweld Model M3 Creep Rupture Machines. The specimen configuration was identical to that used in tensile testing, Figure 36. Temperatures were continuously printed out on a Honeywell temperature recorder. If a sample exceeded 100 hrs. at a given stress, it was step

loaded to failure in increments of 6.89 MN/m^2(1000 psi) to determine the percent elongation.

A larger number of tests were run at 1093°C (2000°F) to examine heat to heat and gauge to gauge variations. The 982°C(1800°F) and 1204°C(2200°F) test results were used along with the 1093°C(2000°F) data to establish the stress range which produces a 100 hr. life.

The test data presented are for samples taken within the 45.7 x 91.4 cm. (18 x 36 in.) sheet. Some 1093°C (2000°F) stress rupture tests were conducted on samples from the offal material at 1093°C(2000°F), but at only two stresses, 37.9 MN/m^2(5.5 ksi) for 0.076 cm.(0.030 in.) and 0.051 cm.(0.020 in.) sheet and 31.0 MN/m^2(4.5 ksi) for 0.025 cm.(0.010 in.) sheet. In every case, the tests exceeded 100 hours.

Tables 47, 48 and 49 summarize the results obtained.

It should be noted that in evaluating stress rupture results, it is necessary to examine time differences of one or two orders of magnitude. There is little difference, for example, between samples with lives of 1 hour and 5 hours at the same stress and temperature.

Heat 3456 at 0.076 cm.(0.030 in.) which, as previously mentioned, had a slightly larger grain size than the other two heats at this gauge, did exhibit better stress rupture strength at 1093°C(2000°F). At 44.7 MN/m^2(6500 psi), no failures occurred in less than 100 hours. The samples from Heats 3415 and

TABLE 47

1093°C(2000°F) STRESS RUPTURE RESULTS FOR REPRODUCIBILITY HEATS

Heat No.	Gauge cm.	Gauge in.	Initial Stress MN/m^2	Initial Stress ksi	Time at Initial Stress Hrs.	Stress at Failure MN/m^2	Stress at Failure ksi	Time at Failure	% Elong.
3415	0.076	0.030	37.6	5.5	111.8	51.7	7.5	118.3	6.5
	0.076	0.030	37.6	5.5	112.5	58.5	8.5	115.1	6.0
	0.076	0.030	44.8	6.5	6.7	44.8	6.5	6.7	6.0
3502	0.076	0.030	37.6	5.5	116.6	51.7	7.5	117.8	7.5
	0.076	0.030	44.8	6.5	1.9	44.8	6.5	1.9	5.6
	0.076	0.030	51.7	7.5	4.0	51.7	7.5	4.0	5.0
	0.076	0.030	37.6	5.5	113.4	51.7	7.5	115.5	15.5
	0.076	0.030	44.8	6.5	115.7	58.5	8.5	117.2	16.0
3456	0.076	0.030	44.8	6.5	112.8	58.5	8.5	114.2	2.5
	0.076	0.030	51.7	7.5	69.3	51.7	7.5	69.3	2.5
	0.076	0.030	37.6	5.5	136.7	86.1	12.5	163.2	5.0
	0.076	0.030	37.6	5.5	136.7	58.5	8.5	140.0	3.0
3415	0.051	0.020	44.8	6.5	136.4	65.4	9.5	139.0	6.5
	0.051	0.020	44.8	6.5	136.3	65.4	9.5	138.9	5.0
	0.051	0.020	51.7	7.5	113.0	65.4	9.5	114.4	2.5
	0.051	0.020	51.7	7.5	21.3	51.7	7.5	21.3	10.0
3502	0.051	0.020	37.6	5.5	112.5	72.4	10.5	117.4	6.5
	0.051	0.020	37.6	5.5	136.8	79.0	11.5	142.5	10.6
	0.051	0.020	44.8	6.5	112.3	65.4	9.5	115.3	5.6
	0.051	0.020	44.8	6.5	112.6	79.0	11.5	117.4	*
3456	0.051	0.020	44.8	6.5	136.6	65.4	9.5	139.1	5.6
	0.051	0.020	44.8	6.5	136.6	79.0	11.5	143.3	6.0
	0.051	0.020	51.7	7.5	96.8	51.7	7.5	96.8	*
	0.051	0.020	51.7	7.5	113.0	65.4	9.5	114.4	6.5

TABLE 47
(CONT'D)

1093°C(2000°F) STRESS RUPTURE RESULTS FOR REPRODUCIBILITY HEATS

Heat No.	Gauge cm.	Gauge in.	Initial Stress MN/m^2	Initial Stress ksi	Time at Initial Stress Hrs.	Stress at Failure MN/m^2	Stress at Failure ksi	Time at Failure	% Elong.
3415	0.025	0.010	37.6	5.5	132.8	37.6	5.5	132.8	5.0
	0.025	0.010	44.8	6.5	147.6	79.0	11.5	152.4	*
	0.025	0.010	51.7	7.5	117.7	51.7	7.5	117.7	6.1
3502	0.025	0.010	37.6	5.5	137.4	51.7	7.5	139.0	*
	0.025	0.010	44.8	6.5	113.8	51.7	7.5	114.1	*
	0.025	0.010	51.7	7.5	185.4	72.4	10.5	188.1	*
3456	0.025	0.010	37.6	5.5	112.8	37.6	5.5	112.8	4.0
	0.025	0.010	44.8	6.5	22.0	44.0	6.5	22.0	*
	0.025	0.010	51.7	7.5	137.4	72.4	10.5	140.2	*

* Sample either broke at pin hole or broke into several pieces.

TABLE 48

982°C(1800°F) STRESS RUPTURE RESULTS FOR REPRODUCIBILITY HEATS

Heat No.	Gauge cm.	Gauge in.	Initial Stress MN/m^2	Initial Stress ksi	Time at Initial Stress Hrs.	Stress at Failure MN/m^2	Stress at Failure ksi	Time at Failure	% Elong.
3415	0.076	0.030	51.7	7.5	112.9	79.0	11.5	117.2	7.5
	0.076	0.030	44.8	6.5	112.9	72.4	10.5	117.2	6.5
	0.076	0.030	58.5	8.5	1.5	58.5	8.5	1.5	3.5
3502	0.076	0.030	58.5	8.5	137.0	79.0	11.5	139.2	11.5
	0.076	0.030	58.5	8.5	142.2	72.4	10.5	143.8	*
	0.076	0.030	65.4	9.5	67.7	65.4	9.5	67.7	10.0
	0.076	0.030	72.4	10.5	.5	72.4	10.5	.5	2.5
	0.076	0.030	79.0	11.5	.4	79.0	11.5	.4	2.0
3456	0.051	0.020	58.5	8.5	137.0	98.5	14.5	142.5	5.6
	0.051	0.020	65.4	9.5	1.0	65.4	9.5	1.0	3.5
	0.051	0.020	72.4	10.5	.5	72.4	10.5	.5	2.5
	0.051	0.020	79.0	11.5	.1	79.0	11.5	.1	6.5
3502	0.025	0.010	58.5	8.5	113.5	98.5	14.5	136.5	7.5
	0.025	0.010	65.4	9.5	115.8	93.0	13.5	118.9	*
	0.025	0.010	72.4	10.5	113.4	98.5	14.5	116.4	*
	0.025	0.010	44.8	6.5	135.9	79.0	11.5	140.9	2.5
	0.025	0.010	51.7	7.5	135.9	65.4	9.5	137.3	2.5

*Sample either broke at pin hole or broke into several pieces.

TABLE 49

1204°C(2200°F) STRESS RUPTURE RESULTS FOR REPRODUCIBILITY HEAT

Heat No.	Gauge cm.	Gauge in.	Initial Stress MN/m^2	Initial Stress ksi	Time at Initial Stress Hrs.	Stress at Failure MN/m^2	Stress at Failure ksi	Time at Failure Hrs.	% Elong.
3415	0.076	0.030	27.6	4.0	97.0	34.4	5.0	97.8	63.0
3415	0.076	0.030	34.4	5.0	238.8	34.4	5.0	238.8	*
3502	0.076	0.030	20.7	3.0	105.7	34.4	5.0	107.8	30.5
3502	0.076	0.030	27.6	4.0	5.2	27.6	4.0	5.2	8.5
3502	0.076	0.030	34.4	5.0	.5	34.4	5.0	.5	4.5
3456	0.076	0.030	27.6	4.0	136.3	48.2	7.0	139.6	4.5
3456	0.076	0.030	34.4	5.0	121.6	41.4	6.0	122.3	4.0
3415	0.051	0.020	27.6	4.0	137.1	48.2	7.0	140.4	55.5
3415	0.051	0.020	34.4	5.0	318.9	34.4	5.0	318.9	*
3502	0.051	0.020	27.6	4.0	101.7	41.4	6.0	116.2	20.5
3502	0.051	0.020	34.4	5.0	113.8	55.1	8.0	124.5	54.0
3456	0.051	0.020	27.6	4.0	102.4	41.4	6.0	128.5	26.5
3456	0.051	0.020	34.4	5.0	138.4	55.1	8.0	143.1	55.0
3415	0.025	0.010	27.6	4.0	138.9	55.1	8.0	142.9	16.5
3415	0.025	0.010	34.4	5.0	102.6	68.9	10.0	144.7	48.0
3502	0.025	0.010	27.6	4.0	160.0	55.1	8.0	165.6	34.5
3502	0.025	0.010	34.4	5.0	93.4	34.4	5.0	93.4	*
3456	0.025	0.010	27.6	4.0	136.7	48.2	7.0	140.5	14.5
3456	0.025	0.010	34.4	5.0	26.2	34.4	5.0	26.2	4.5

*Sample either broke at pin hole or broke into several pieces.

3502 did fail in less than 100 hours. A stress of 37.9 MN/m^2 (5500 psi) produced lives in excess of 100 hours in every test on 0.076 cm.(0.030 in.) sheet.

All heats appear to be equivalent at 0.051 cm. (0.020 in.), having a stress slightly greater than 44.7 MN/m^2 (6500 psi) for failure over 100 hours.

At 0.025 cm.(0.010 in.) all specimens withstood a stress of 51.6 MN/m^2 (7500 psi) for greater than 100 hours. However, since there were two cases in which failure occurred shortly after 100 hours at 37.9 MN/m^2 (5500 psi), this stress is a reasonable lower limit.

It appears, that, 0.051 cm.(0.020 in.) sheet is the strongest gauge, while 0.076 cm.(0.030 in.) and 0.025 cm. (0.010 in.) sheet are equivalent in stress rupture strength.

The stress levels at 982°C(1800°F) average 13.8-20.7 MN/m (2-3 ksi) above those at 1093°C(2000°F). A conservative lower limit is between 51.6 MN/m^2 (7500 psi) and 55.0 MN/m^2 (8000 psi) for 100 hour life at 982°C(1800°F).

The 1204°C(2200°F) results show the same gauge to gauge trends. The 0.051 cm.(0.020 in.) sheet withstood a stress of 34.4 MN/m^2 (5.0 ksi) for 100 hours in all tests, while 0.076 cm.(0.030 in.) and 0.025 cm.(0.010 in.) sheet failed in several cases at this stress. One case of one heat, 3502, at 0.076 cm.(0.030 in.), did not exceed 100 hours at 27.6 MN/m^2 (4.0 ksi). It did, however, pass 100 hours at 20.7 MN/m^2 (3.0 ksi).

Percent elongations at fracture average well above those found in tensile tests at 1093°C(2000°F). The average elongation in tensile testing was approximately 3%, and that in stress rupture testing, 6%.

Stress rupture data are best presented in a Larsen Miller plot, which is a semi-log plot of the Larsen Miller Parameter P and the stress. P is defined as

$$P = (T + 273)\ (\log t + k) \text{ ------(T in } ^\circ C)$$

$$\text{or } P = (T + 460)\ (\log t + k) \text{ ------(T in } ^\circ F)$$

where:

P = Larsen Miller Parameter

T = Temperature (°C or °F)

t = time in hours

k = Constant. For TDNiCr, k = 34 (Independent of temperature)

This parameter permits presentation of three variables, stress, temperature and time, on one curve.

Figures 53, 54 and 55 are Larsen Miller plots of 0.076 cm, 0.051 cm. and 0.025 cm. (0.030 in., 0.020 in. and 0.010 in.) sheet respectively. The Larsen Miller Parameters for 100 hour lives at 982°C, 1093°C and 1204°C (1800°F, 2000°F and 2200°F) have been notated on the abcissa. Points with arrows indicate that the sample was step loaded to failure. In many cases, there were several data points at the same location. However, for clarity, only one is presented.

The stress rupture life at different temperatures and stresses can easily be found by calculating P and referring to these curves.

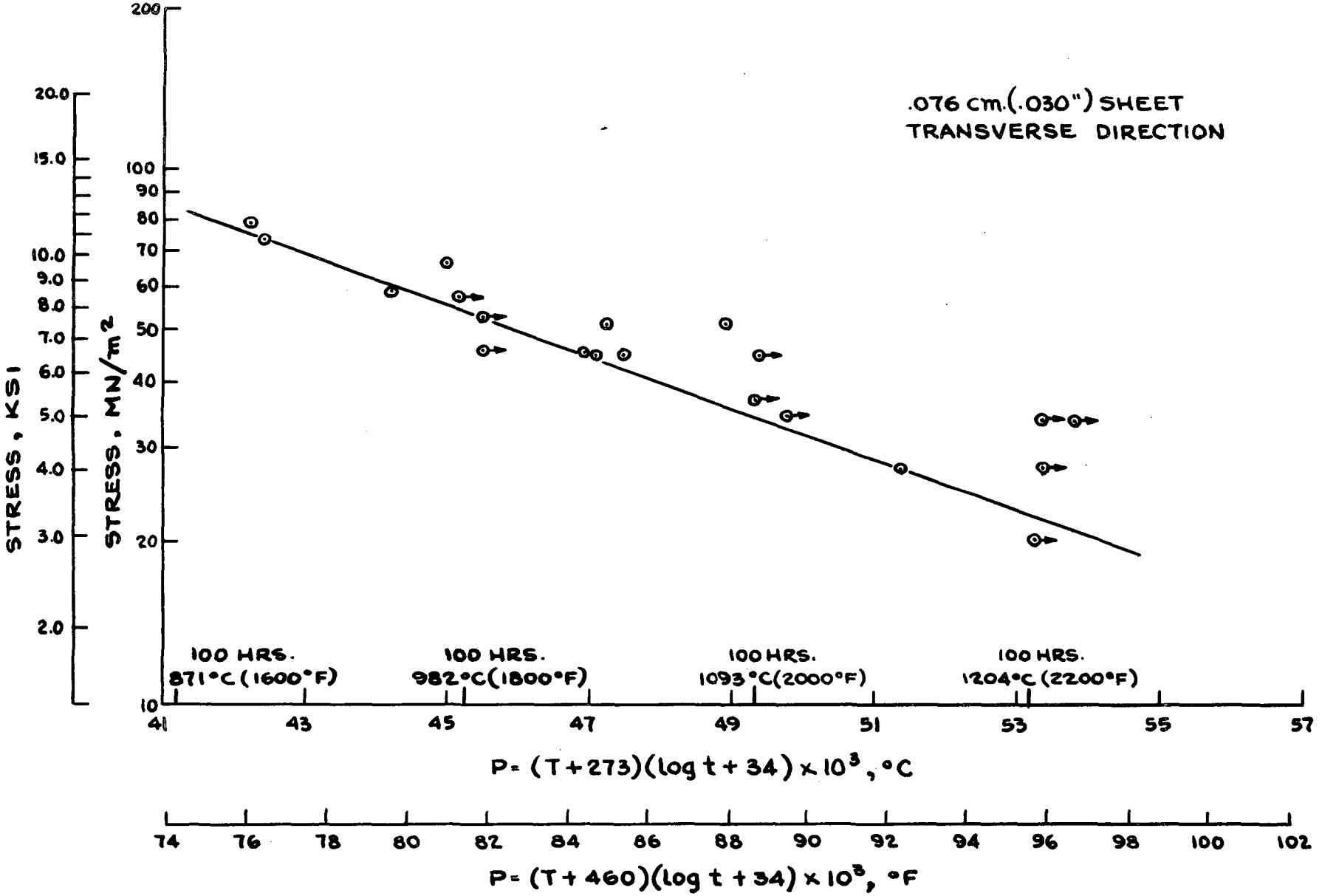


FIGURE 53

LARSEN MILLER PLOTS FOR TDNiCr SHEET

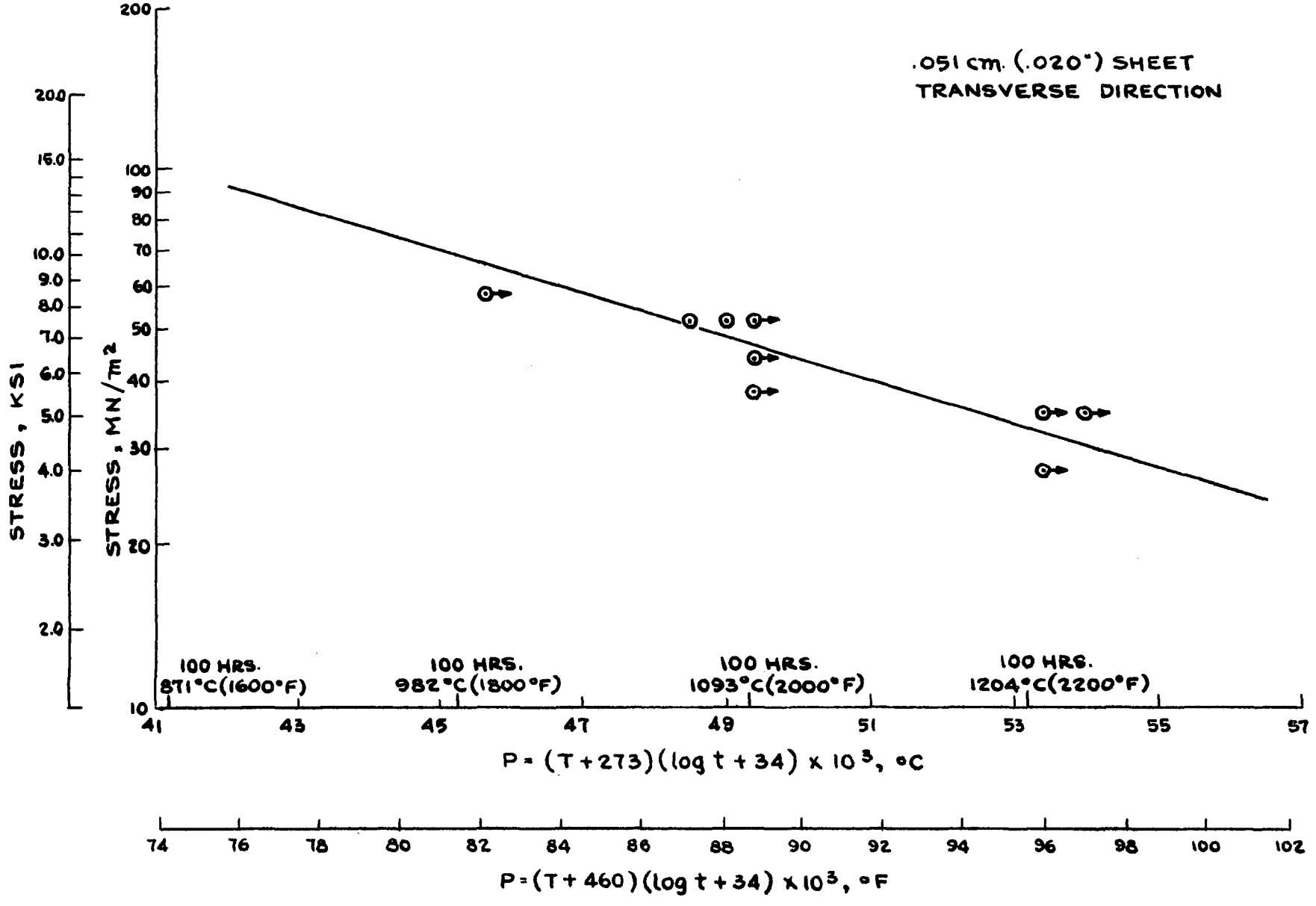


FIGURE 54

LARSEN MILLER PLOTS FOR TDNiCr SHEET

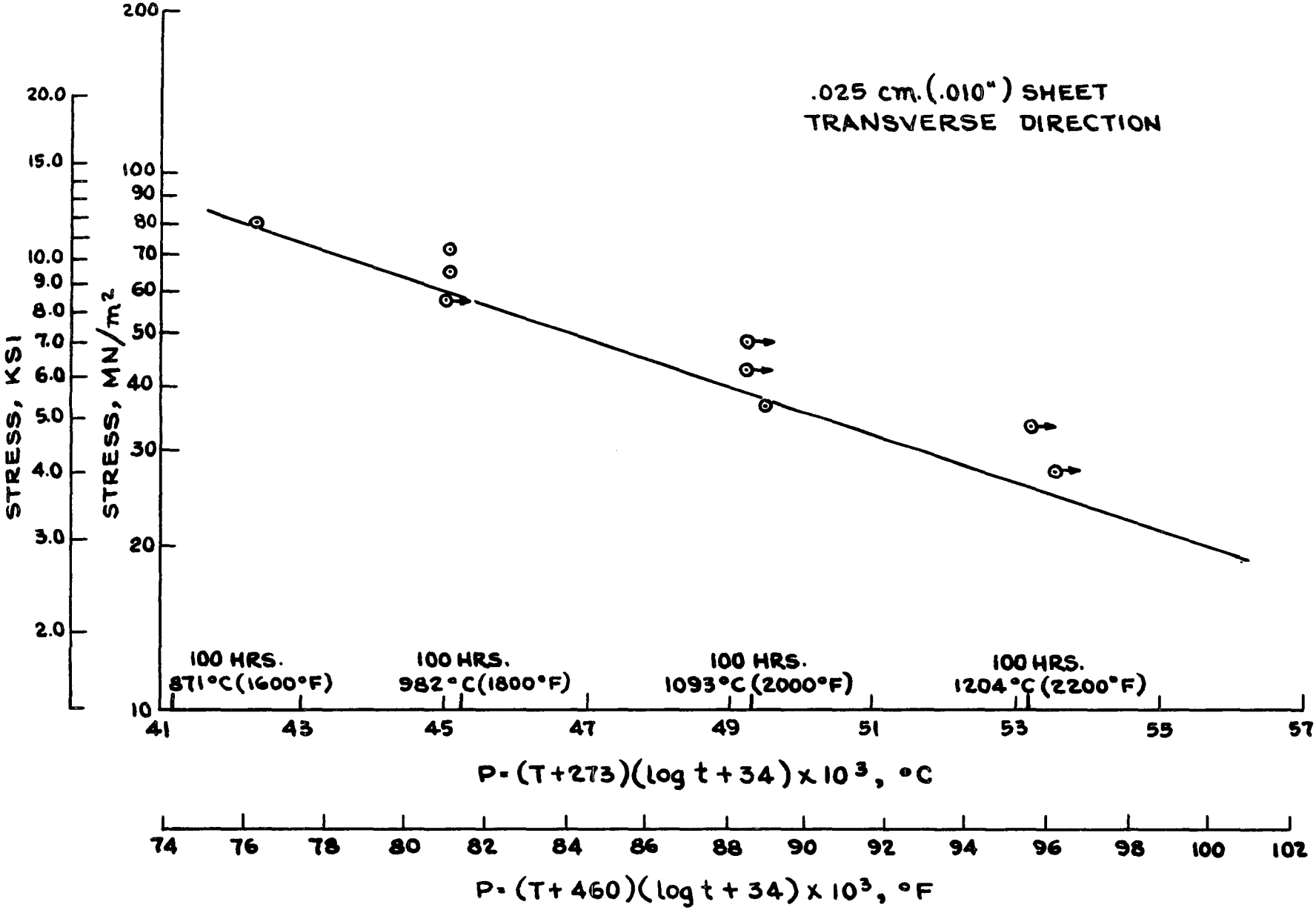


FIGURE 55

LARSEN MILLER PLOTS FOR TDNiCr SHEET

(3.) Creep

A number of creep tests were conducted on the reproducibility series of heats and gauges to determine the stress to produce 0.5% creep in 100 hours at 1093°C(2000°F). In addition, the results were utilized to compare reproducibility between heats. It was found that the typical stress to produce 0.5% creep lies between 27.6 MN/m^2 and 34.5 MN/m^2 (4.0 and 5.0 ksi) in the transverse direction. Several longitudinal tests indicated that a 50% increase can be expected over the transverse direction. Comparisons of data spread were made with available superalloy data in MIL-HDBK-5*. TDNiCr exhibits approximately the same scatter as the commercially produced alloys.

Three testing laboratories participated in this portion of the reproducibility evaluation. They were Fansteel, Metcut Research Associates of Cincinnati, Ohio and Battelle Memorial Institute of Columbus, Ohio. A brief summary of the test techniques employed by the three laboratories follows.

- Battelle Memorial Institute, Columbus, Ohio. The Battelle procedure includes:
  - A 2.54 cm.(one inch) gauge length and 0.635 cm.(1/4 in.) gauge width.
  - An optical system for measuring creep strain on two sides of the specimen.

---

*METALLIC MATERIALS AND ELEMENTS FOR FLIGHT VEHICLE STRUCTURES, D.O.D. Military Handbook, MIL-HDBK-5, January 5, 1970.

- Universal joints for maintaining axiality.
- A specimen configuration suitable for pin loading.

Battelle currently prefers to use a platinum strip extensometer welded to the shoulders of the specimen. Battelle is in the process of phasing out the optical system however, and replacing it with Linear Variable Differential Transformers (LVDT's). They were unable to utilize LVDT's for this work, although their use is recommended for later work on the program. One obvious advantage of this sytem is that it provides continuously recorded strain measurements. It was claimed that increased sensitivity, accuracy, and less scatter, particularly in the primary creep region, are obtained. The LVDT system is an electromechanical one and works on the following principle: a magnetically soft iron core, which is mechanially coupled to the specimen, moves in the coils of the differential transformer and causes a corresponding linear change in the demodulated output voltage from the secondary windings of the transformer. The output voltage is printed out on a millivolt recorder as a function of time. A scale factor is used to convert voltage to percent strain.

- Metcut Research Associates, Inc., Cincinnati, Ohio.

  Metcut has the capability to test with a variety of techniques. Various types of extensometers, specimen configurations, systems for strain measurements, etc. are available. They recommended that an optical system be utilized for the work. Although they do have the LVDT system, they prefer to use it only for long time creep tests. Platinum slide extensometers tend to pit after extended periods of time, thereby making strain measurements difficult. Metcut stated that the LVDT's are subject to unknown electronic drift and introduce an added stress due to the weight of the rods which couple the specimen to the LVDT.

  All of the test parameters (grips, gauge length and pull rods) outlined for Battelle are utilized by Metcut also.

- Fansteel Inc.

  Creep testing at Fansteel was performed on Arcweld Model M3 Creep Rupture machines. An optical system designed for use with these machines was being utilized for Part I of this program. However, an LVDT system is under investigation for future work.

The available furnaces have only one 0.635 cm.(1/4 in.) diameter viewing port, which therefore prohibits utilization of platinum slide extensometers on two sides of a specimen. Instead, an extensometer similar to that used by NASA was utilized. Two platinum wires formed into an "L" shape were attached to each side of the specimen so that elongation was measured over the 2.54 cm.(one inch) gauge length. The small leg, which is fixed perpendicular to the loading axis, extends beyond the gauge width so that readings may be made on it with the microscope. This arrangement permits strain readings to be taken on both sides of the specimen within a 0.635 cm.(1/4 in.) field of view. It has been verified that neither creep nor thermal distortion of the wires occurs at 1093° C (2000° F).

Specimens to be tested at Battelle, Metcut and Fansteel from the reproducibility series of TDNiCr sheets are shown in Table 50. As indicated the specimens were secured from 2.70 cm. x 45.7 cm.(1-1/16 x 18 in.) transverse samples. Because of the necessity of cross checking test results of the three test sources, the samples were secured from a 45.7 cm. x 88.9 cm. (18 x 36 in.) sheet of each gauge from each heat.

TABLE 50

REPRODUCIBILITY CREEP TEST SPECIMENS

Heat No.	Gauge cm.	Gauge in.	Battelle	Metcut	Fansteel
3456	0.025	0.010		x	x
3456	0.051	0.020	x x	x x	x
3456	0.076	0.030	x		
3415	0.025	0.010		x	
3415	0.051	0.020		x	
3415	0.076	0.030		x	x
3502	0.025	0.010		x	x
3502	0.051	0.020	x		
3502	0.076	0.030	x	x	x

x - Represents one 2.70 x 45.7 cm. (1-1/16 x 18 in.) transverse sample from which two creep specimens were procured.

Table 51 is a summary of the results obtained. It contains heat numbers, gauge, stress level, testing lab., percent creep at 100 hours and the minimum creep rate. It appears that the stress at 1093°C(2000°F) to produce 0.5% lies between 27.6 and 34.5 MN/m^2 (4.0 and 5.0 ksi). The average percent creep at 27.6 MN/m^2 (4 ksi) was 0.28% and at 34.5 MN/m^2 (5 ksi) 1.74%. Several samples at 0.025 cm.(0.010 in.) and 0.076 cm.(0.030 in.) went into third stage creep at the higher stress level, and therefore exhibit a large percent creep at 100 hours. The large values were characterized by intergranular cracking throughout the gauge length of the specimen. The known transition points (the percent creep at which third stage initiated) are listed below. All are at 34.5 MN/m^2 (5.0 ksi).

Heat No.	Gauge cm.	Gauge in.	Test Lab.	Transition Point
3502	0.076	0.030	Metcut	.75%
3502	0.076	0.030	Battelle	.75%
3415	0.076	0.030	Metcut	1.42%
3415	0.025	0.010	Metcut	1.50%

A statistical analysis was attempted on these data, but there are too few points to satisfy the Chi Square test for determination of the type of distribution. However, a comparison of data at the 27.6 MN/m^2 (4 ksi) stress level with available data for two superalloys (Rene' 41 and Haynes 25), at the same percent creep, Table 52, shows that TDNiCr is comparable in reproducibility. Only 27.6 MN/m^2 (4.0 ksi) data have been used, since at 34.5 MN/m^2 (5.0 ksi) several samples went

TABLE 51

TRANSVERSE CREEP RESULTS FOR TDNiCr SHEET AT 1093°C(2000°F)

Heat No.	Gauge cm.	Gauge in.	Stress MN/m^2	Stress ksi	Tester	% Creep 100 Hrs.	Minimum Creep Rate % per hr. x 10^{-2}
3456	0.025	0.010	27.6	4	Fansteel	.17, .08	.10, .05
3456	0.025	0.010	27.6	4	Metcut	.055	.04
3456	0.025	0.010	34.5	5	Fansteel	.20, .30	.17, .23
3456	0.025	0.010	34.5	5	Metcut	.11	.10
3456	0.051	0.020	27.6	4	Fansteel	.05	.02
3456	0.051	0.020	27.6	4	Metcut	.105	.03
3456	0.051	0.020	27.6	4	Metcut	.10	.03
3456	0.051	0.020	27.6	4	Battelle	.128	.09
3456	0.051	0.020	27.6	4	Battelle	.076	.04
3456	0.051	0.020	34.5	5	Fansteel	.21	.17
3456	0.051	0.020	34.5	5	Metcut	.30	.20
3456	0.051	0.020	34.5	5	Metcut	.18	.16
3456	0.051	0.020	34.5	5	Battelle	.424	.20
3456	0.051	0.020	34.5	5	Battelle	.448	.43
3456	0.076	0.030	27.6	4	Battelle	.212	.06
3456	0.076	0.030	34.5	5	Battelle	.108	.04
3502	0.025	0.010	27.6	4	Fansteel	.11	.08
3502	0.025	0.010	27.6	4	Metcut	.70	.66
3502	0.025	0.010	34.5	5	Fansteel	.91	.49
3502	0.025	0.010	34.5	5	Metcut	.59	.54
3502	0.051	0.020	27.6	4	Battelle	.384	.12
3502	0.051	0.020	34.5	5	Battelle	.480	.26
3502	0.076	0.030	27.6	4	Fansteel	.30	.27
3502	0.076	0.030	27.6	4	Battelle	.200	.02
3502	0.076	0.030	27.6	4	Metcut	.275	.20
3502	0.076	0.030	34.5	5	Fansteel	1.25	1.10
3502	0.076	0.030	34.5	5	Metcut	4.5	1.40
3502	0.076	0.030	34.5	5	Battelle	11.43	2.6
3415	0.025	0.010	27.6	4	Metcut	.34	.18
3415	0.025	0.010	34.5	5	Metcut	3.8	2.8
3415	0.051	0.020	27.6	4	Metcut	.45	.24
3415	0.051	0.020	34.5	5	Metcut	.155	.09
3415	0.076	0.030	27.6	4	Fansteel	.56, .60	.42, .55
3415	0.076	0.030	27.6	4	Metcut	.75	.64
3415	0.076	0.030	34.5	5	Fansteel	2.10, 1.25	1.10, .84
3415	0.076	0.030	34.5	5	Metcut	6.25	3.6

TABLE 52

COMPARISON OF TDNiCr CREEP DATA WITH TWO SUPERALLOYS

Alloy	Gauge cm.	Gauge in.	Stress MN/m^2	Stress ksi	Temp. °C	Temp. °F	Average* Percent Creep	2σ Limits
Haynes 25	.051-.203	.020-.080	15.2	2.2	982	1800	.28%	.08%-.90%
Rene' 41	.051-.203	.020-.080	5.93	.86	982	1800	.28%	.09%-.78%
TDNiCr	.025-.076	.010-.030	27.6	4.0	1093	2000	.28%	.06%-.75%**

* Percent creep in 100 hrs. at 982°C(1800°F) for superalloys, 1093°C(2000°F) for TDNiCr.

** Calculations of 2σ limits not possible. Values given are maximum and minimum percent creep in 100 hrs. for 20 tests.

into third stage creep. When this occurs, a large increase in percent creep occurs over a short period of time prior to failure.

The data presented in Table 52 were obtained from MIL-HDBK-5. Rene' 41 and Haynes 25 were chosen because no such data were available for other superalloys. The 2σ limits are the creep percents within which 95% of all tests will fall. It should be noted that data for these alloys were taken at 982°C(1800°F). Data are not available at 1093°C(2000°F).

In addition to the above tests on the transverse direction, creep tests were conducted on the longitudinal direction by Fansteel. Table 53 presents the results, which indicate that approximately a 50% increase can be expected.

(4.) Bend Tests

Bend tests were conducted on each heat and each gauge of the reproducibility series of heats in accordance with Fansteel Specification S-TC-S-01-R-1, which states that "the material shall withstand, without cracking, bending at room temperature through an angle of 105° around a radius equal to the bend factor (3.0) times the nominal thickness of the material." Specimens were tested with both "as received" and polished surfaces. "As received" consisted of a ground finish (wide belt sanded) of less than 32 rms. Edges of the specimen were rounded to prevent initiation of cracks at sharp corners. Polishing was performed through 240 and 400 grit papers on the surface and edges. Specimen dimensions were gauge x 1.9 x 5.1 cm.(gauge x 3/4 x 2 in.). Both sides of each specimen were subjected to bending. Samples were procured at angles of 0°, 45° and 90° to the rolling direction.

TABLE 53

LONGITUDINAL CREEP DATA FOR TDNiCr AT 1093°C(2000°F) AND 100 HRS.

Heat No.	Gauge cm.	Gauge in.	Stress MN/m^2	Stress ksi	% Creep at 100 Hrs.
3415	0.025	0.010	41.4	6.0	.11
3456	0.051	0.020	41.4	6.0	.28
3502	0.025	0.010	41.4	6.0	.22
3415	0.025	0.010	37.9	5.5	.14

The samples used were as follows (Refer to Figure 31.):

Transverse - Samples 70-82, 75-104

Longitudinal - Samples 82-94

45° - Samples 119-128, 135-140

Table 54 is a summary of the results obtained. All heats and gauges met the Fansteel specification for minimum bend radius.

Differences existed in the minimum bend radius between the 45° and longitudinal directions, and the transverse direction. In all cases the 45° and longitudinal were equivalent and less than 1T. The transverse direction, however, varied from 2T to 3T. Since a variation was observed only in this direction, the discussion of the variability is limited to transverse testing only.

Heat 3456 at 0.076 cm.(0.030 in.) which was observed to have a slightly larger grain size than the other two heats at this gauge, had a minimum bend radius approximately 1T larger, (3T vs. 2T). This difference, however, was not observed for this heat at either of the two thinner gauges where grain sizes at each gauge were equivalent for each heat.

A larger minimum bend radius was observed for 0.025 cm.(0.010 in.) than for 0.051 cm.(0.020 in.) sheet (3T vs. 2T). This difference, cannot necessarily be attributed to the slight difference in grain size previously mentioned. Because of a limited number of bend dies, testing was at either 3T or 1.5T for 0.025 cm.(0.010 in.) sheet, i.e., intermediate bend radius of 2.0T, for example, could be tested.

TABLE 54

BEND TEST RESULTS FOR REPRODUCIBILITY HEATS & GAUGES

Heat No.	Gauge cm.	Gauge in.	Surface Condition	Direction	Min. Bend Radius
3415	0.076	0.030	Ground	Trans.	3.1T
	0.076	0.030	Ground	45°	.5T
	0.076	0.030	Ground	Long.	.5T
	0.076	0.030	Polished	Trans.	2.1T
	0.076	0.030	Polished	45°	.5T
	0.076	0.030	Polished	Long.	.5T
3415	0.051	0.020	Ground	Trans.	3.0T
	0.051	0.020	Ground	45°	.8T
	0.051	0.020	Ground	Long.	.8T
	0.051	0.020	Polished	Trans.	2.3T
	0.051	0.020	Polished	45°	.8T
	0.051	0.020	Polished	Long.	.8T
3415	0.025	0.010	Ground	Trans.	3.0T
	0.025	0.010	Ground	45°	.7T
	0.025	0.010	Ground	Long.	.7T
	0.025	0.010	Polished	Trans.	3.0T
	0.025	0.010	Polished	45°	.7T
	0.025	0.010	Polished	Long.	.7T
3456	0.076	0.030	Ground	Trans.	3.5T
	0.076	0.030	Ground	45°	.5T
	0.076	0.030	Ground	Long.	.5T
	0.076	0.030	Polished	Trans.	3.0T
	0.076	0.030	Polished	45°	.5T
	0.076	0.030	Polished	Long.	.5T
3456	0.051	0.020	Ground	Trans.	3.0T
	0.051	0.020	Ground	45°	.8T
	0.051	0.020	Ground	Long.	.8T
	0.051	0.020	Polished	Trans.	2.3T
	0.051	0.020	Polished	45°	.8T
	0.051	0.020	Polished	Long.	.8T
3456	0.025	0.010	Ground	Trans.	3.0T
	0.025	0.010	Ground	45°	.7T
	0.025	0.010	Ground	Long.	.7T
	0.025	0.010	Polished	Trans.	3.0T
	0.025	0.010	Polished	45°	.7T
	0.025	0.010	Polished	Long.	.7T

TABLE 54
(Cont'd)

BEND TEST RESULTS FOR REPRODUCIBILITY HEATS & GAUGES

Heat No.	Gauge cm.	Gauge in.	Surface Condition	Direction	Min. Bend Radius
3502	0.076	0.030	Ground	Trans.	3.5T
	0.076	0.030	Ground	45°	.5T
	0.076	0.030	Ground	Long.	.5T
	0.076	0.030	Polished	Trans.	2.1T
	0.076	0.030	Polished	45°	.5T
	0.076	0.030	Polished	Long.	.5T
3502	0.051	0.020	Ground	Trans.	3.0T
	0.051	0.020	Ground	45°	.8T
	0.051	0.020	Ground	Long.	.8T
	0.051	0.020	Polished	Trans.	2.3T
	0.051	0.020	Polished	45°	.8T
	0.051	0.020	Polished	Long.	.8T
3502	0.025	0.010	Ground	Trans.	3.0T
	0.025	0.010	Ground	45°	.7T
	0.025	0.010	Ground	Long.	.7T
	0.025	0.010	Polished	Trans.	3.0T
	0.025	0.010	Polished	45°	.7T
	0.025	0.010	Polished	Long.	.7T

Polishing was shown to be an aid in lowering the minimum bend radius in some cases producing improvements of greater than 1T better than for the "as-received" condition.

A goal of 2T had been established for minimum bend radius. Development of the standard process for sheet during the past year has shown that to consistently meet a 2T minimum bend, a sacrifice in stress rupture strength is necessary. The 3T bend radius has therefore been maintained as the bend requirement for Part II of the program.

(5.) Formability

Cup testing was employed as a means of attempting to evaluate room temperature formability of the three heats at three different gauges for the reproducibility series. This type of test combined with the bend data and room temperature elongation given an appraisal of the formability of the TDNiCr sheet.

A Mohr and Federhoff Cup Tester was employed for this evaluation. The objective was to determine the load required to initial fracture and resultant cup depth obtained. Each gauge from each of the three reproducibility heats was evaluated. The results are shown in Table 55. It may be noted from these data that very little difference in depth of cup was encountered as a result of gauge. However, these data tend to be misleading because determination of point of initial fracture is very difficult to observe with thin sheet. For example, as gauge decreases, stopping the test at initial fracture becomes more difficult, thus increasing the resultant drawn cup depth.

TABLE 55

TDNiCr SHEET CUP TESTING RESULTS

Heat No.	Gauge		Breaking Load		Cup Depth	
	cm.	in.	kg	lb.	cm.	in.
3415-23	0.025	0.010	363	800	0.437	0.172
3456-22	0.025	0.010	227	500	0.358	0.141
3502-24	0.025	0.010	318	700	0.478	0.188
3415-13	0.051	0.020	726	1600	0.437	0.172
3456-6	0.051	0.020	817	1800	0.478	0.188
3502-2	0.051	0.020	817	1800	0.478	0.188
3415-12	0.076	0.030	1362	3000	0.554	0.218
3456-9	0.076	0.030	1362	3000	0.554	0.218
3502-4	0.076	0.030	1362	3000	0.516	0.203

Despite this effect, the test does show quite reproducible values for cup depth and breaking load from heat to heat for any specific gauge.

It should, also, be pointed out that change of grain size does not appear to change cup depth and/or breaking load as indicated by Heat 3456 at 0.076 cm.(0.030 in.). This sheet was reported to have an average grain size approximately two times that of Heat 3415 and Heat 3502.

(6.) Oxidation Tests - 1204° C(2200° F)

A 50 hour rig test at 1204° C(2200° F) was performed with TDNiCr specimens from the reproducibility study to determine whether a heat to heat or gauge to gauge variation exists. The test technique employed is described in a later section of this report on Alloy Studies.

The specimens represented were 0.025 and 0.076 cm.(0.010 and 0.030 in.) thicknesses from Heats 3415, 3456 and 3502. In all instances the onset of accelerated attack occurred in a shorter period of time for the thinner gauge specimens, the heavier stock having a greater reservoir of Cr. Porosity was restricted to the surfaces of the 0.076 cm. (0.030 in.) stock whereas it extended into the thinner specimens.

4. Production of 680.4 kg.(1500 lbs.) of TDNiCr Sheet

Exhibit A of the contract specified that fifty 45.36 kg. (100 lb.) forged sheet bars were to be manufactured for the production of at least 680.4 kg.(1500 lbs.) of TDNiCr sheet. However, since production of this sheet was to be carried out concurrently with process development studies, processing schedules

were altered accordingly with the approval of the NASA Project Manager. Table 56 itemizes the heats employed for this requirement with appropriate processing history.

The first five heats processed utilized the forge consolidation route of processing while the balance of the heats were consolidated utilizing the rolling route. A total of 52 - 45.36 kg.(100 lb.) units and 7 - 68.04 kg.(150 lb.) units were employed to satisfy this requirement. The 7 - 68.04 kg.(150 lb.) units were secured from a portion of the material utilized for the sheet size scale-up study carried out in the Sheet Process Development study.

Table 56 also indicates the starting unit weight and respective finished product shipped accordingly. These weights, however, cannot be construed as true yields in all cases because portions of material from certain heats were diverted to use for other purposes of a developmental nature.

For example, portions of Heats 3435 and 3436 were utilized to determine effect of isothermal rolling temperature and recrystallization temperature upon structure and properties. Further, Heat 3473 was one of the first units to be checked at the 2.54 cm. (1.0 in.) slab stage for thoria size and subsequently given a 1177° C(2150° F) heat treatment for two hours followed by rolling to a finish gauge of 0.102 and 0.025 cm.(0.040 and 0.010 in.). The majority of this heat was lost since the 0.102 cm.(0.040 in.) stress rupture results were found to be marginal. Finally, the 7 - 68.04 kg.(150 lb.) heats were utilized for sheet size scale-up studies and therefore higher losses were experienced due to work being carried out during early stages of the learning curve.

TABLE 56

PRODUCTION HEATS OF TDNiCr AND PROCESSING HISTORY

Heat No.	Gauge cm.	Sinter Temp.	Consolidation Method	Consolidation Temp.	ThO_2 Size Heat Treat	760°C Roll, Can Mat'l.	Starting Unit kg.	Shipped kg.
3321	0.051	954°C	Forge	1010°C	None	Mild Steel	45.36	21.55
	0.203							
3322	0.025	954°C	Forge	1010°C	None	Mild Steel	44.46	14.61
	0.038	954°C						
	0.102	954°C						
	0.152	954°C						
3323	0.038	954°C	Forge	1010°C	None	Mild Steel	45.36	18.05
	0.064	954°C						
3324	0.025	954°C	Forge	1010°C	None	Mild Steel	45.36	12.75
	0.038							
	0.127	954°C						
3325	0.152	954°C	Forge	1010°C	None	Mild Steel	45.36	20.91
	0.635							
3387	0.025	954°C	Roll	1066°C	None	Mild Steel	45.36	10.16
3382	0.025	954°C	Roll	1066°C	None	Mild Steel	45.36	6.62
3416	0.025	954°C	Roll	1010°C	None	Mild Steel	45.36	15.51
3384	0.635	954°C	Roll	1010°C	None	Mild Steel	45.36	13.93
3361	0.038	954°C	Roll	1010°C	None	Mild Steel	45.36	13.56
3472	0.699	954°C	Roll	1010°C	None	Mild Steel	50.0	24.22
3419	0.025	954°C	Roll	1010°C	None	Mild Steel	45.36	10.84
3414	0.025	954°C	Roll	1010°C	None	Mild Steel	45.48	8.44
3435	0.025	954°C	Roll	1010°C	None	Mild Steel	45.36	11.11
3436	0.025	954°C	Roll	1010°C	None	Mild Steel	45.36	8.66
3493	0.051	954°C	Roll	1010°C	1177°C	Mild Steel	45.52	18.01
3510	0.051	954°C	Roll	1010°C	1177°C	Mild Steel	45.36	17.24
3507	0.051	1177°C	Roll	1177°C	None	Mild Steel	45.36	19.73
	0.102	1177°C		1177°C				
3473	0.025	954°C	Roll	1010°C	1177°C	Mild Steel	45.36	7.53
	0.102	954°C						
3516	0.051	954°C	Roll	1010°C	1177°C	Mild Steel	45.36	16.15
3499	0.051	954°C	Roll	1010°C	1177°C	Mild Steel	45.36	17.33
3494	0.051	954°C	Roll	1010°C	1177°C	Mild Steel	45.52	16.47
3508	0.076	954°C	Roll	1010°C	1177°C	Mild Steel	45.36	17.42
3501	0.076	954°C	Roll	1010°C	1177°C	Mild Steel	45.36	19.23

TABLE 56

PRODUCTION HEATS OF TDNiCr AND PROCESSING HISTORY

Heat No.	Gauge in.	Sinter Temp.	Consolidation Method	Consolidation Temp.	ThO_2 Size Heat Treat	1400°F Roll. Can Mat'l	Starting Unit lbs.	Shipped lbs.
3321	0.020 0.080	1750°F	Forge	1850°F	None	Mild Steel	100.0	47.5
3322	0.010 0.015 0.040 0.060	1750°F	Forge	1850°F	None	Mild Steel	98.0	32.3
3323	0.015 0.025	1750°F	Forge	1850°F	None	Mild Steel	100.0	39.8
3324	0.010 0.015 0.050	1750°F	Forge	1850°F	None	Mild Steel	100.0	28.1
3325	0.060 0.250	1750°F	Forge	1850°F	None	Mild Steel	100.0	46.1
3387	0.010	1750°F	Roll	1950°F	None	Mild Steel	100.0	22.4
3382	0.010	1750°F	Roll	1950°F	None	Mild Steel	100.0	14.6
3416	0.010	1750°F	Roll	1850°F	None	Mild Steel	100.0	34.2
3384	0.250	1750°F	Roll	1850°F	None	Mild Steel	100.0	30.7
3361	0.015	1750°F	Roll	1850°F	None	Mild Steel	100.0	29.9
3472	0.275	1750°F	Roll	1850°F	None	Mild Steel	110.5	53.4
3419	0.010	1750°F	Roll	1850°F	None	Mild Steel	100.0	23.9
3414	0.010	1750°F	Roll	1850°F	None	Mild Steel	100.4	18.7
3435	0.010	1750°F	Roll	1850°F	None	Mild Steel	100.0	24.5
3436	0.010	1750°F	Roll	1850°F	None	Mild Steel	100.0	19.1
3493	0.020	1750°F	Roll	1850°F	2150°F	Mild Steel	100.5	39.7
3510	0.020	1750°F	Roll	1850°F	2150°F	Mild Steel	100.0	38.0
3507	0.020 0.040	2150°F	Roll	2150°F	None	Mild Steel	100.0	43.5
3473	0.010 0.040	1750°F	Roll	1850°F	2150°F	Mild Steel	100.0	16.6
3516	0.020	1750°F	Roll	1850°F	2150°F	Mild Steel	100.0	35.6
3499	0.020	1750°F	Roll	1850°F	2150°F	Mild Steel	100.0	38.2
3494	0.020	1750°F	Roll	1850°F	2150°F	Mild Steel	100.5	36.3
3508	0.030	1750°F	Roll	1850°F	2150°F	Mild Steel	100.0	38.4
3501	0.030	1750°F	Roll	1850°F	2150°F	Mild Steel	100.0	42.4

TABLE 56 (CONT'D)

PRODUCTION HEATS OF TDNiCr AND PROCESSING HISTORY

Heat No.	Gauge cm.	Sinter Temp.	Consolidation Method	Consolidation Temp.	ThO_2 Size Heat Treat	760°C Roll. Can Mat'l.	Starting Unit kg.	Shipped kg.
3514	0.038	954°C	Roll	1010°C	1177°C	Mild Steel	45.36	16.78
3511	0.038	954°C	Roll	1010°C	1177°C	Mild Steel	45.36	16.33
3509	0.102	954°C	Roll	1010°C	1177°C	Mild Steel	45.36	19.82
3515	0.102	954°C	Roll	1010°C	1177°C	Mild Steel	45.36	21.00
3517	0.051	954°C	Roll	1010°C	1177°C	Mild Steel	45.36	15.20
3512	0.076	954°C	Roll	1010°C	1177°C	Mild Steel	45.36	3.18
3513	0.076	954°C	Roll	1010°C	1177°C	Mild Steel	45.36	11.93
3359	0.203	954°C	Roll	1010°C	None	Mild Steel	45.36	16.69
3496	0.312	954°C	Roll	1010°C	None	Mild Steel	45.36	6.89
3518	0.051	954°C	Roll	1010°C	1177°C	Mild Steel	45.36	7.62
3622	0.076	954°C	Roll	1010°C	1093°C	Al. Steel	45.36	24.13
3638	0.076	954°C	Roll	1010°C	1093°C	Al. Steel	45.32	22.14
3639	0.076	954°C	Roll	1010°C	1093°C	Al. Steel	45.36	19.73
3626	0.076	954°C	Roll	1010°C	1093°C	Al. Steel	45.36	21.82
3455	0.203	954°C	Roll	1010°C	None	Al. Steel	45.23	9.48
3629	0.051	954°C	Roll	1010°C	1093°C	Al. Steel	45.36	8.21
3636	0.051 0.038	954°C	Roll	1010°C	1093°C	Al. Steel	45.36	14.65
3628	0.076	954°C	Roll	1010°C	1093°C	Al. Steel	45.36	14.83
3623	0.102	1121°C	Roll	1121°C	None	Al. Steel	45.32	25.72
3624	0.102	1177°C	Roll	1177°C	None	Al. Steel	45.32	21.23
3640	0.051 0.038	954°C	Roll	1010°C	1093°C	Al. Steel	45.36	17.15
3630	0.051 0.038	954°C	Roll	1010°C	1093°C	Al. Steel	45.36	15.83
3632	0.025	954°C	Roll	1010°C	1093°C	Al. Steel	45.36	4.13
3634	0.025	954°C	Roll	1010°C	1093°C	Al. Steel	45.36	10.21
3635	0.025	954°C	Roll	1010°C	1093°C	Al. Steel	45.36	15.65
3637	0.025	954°C	Roll	1010°C	1093°C	Al. Steel	45.36	2.49
3453	0.254	954°C	Roll	1010°C	None	Al. Steel	45.18	11.93
3627	0.025	954°C	Roll	1010°C	1093°C	Al. Steel	45.36	5.44
3520	0.025	954°C	Roll	1010°C	1093°C	Al. Steel	68.04	8.48
3523	0.025	954°C	Roll	1010°C	1093°C	Al. Steel	68.04	9.80
3526	0.025	954°C	Roll	1010°C	1093°C	Al. Steel	68.04	17.92

TABLE 56 (CONT'D)

PRODUCTION HEATS OF TDNiCr AND PROCESSING HISTORY

Heat No.	Gauge in.	Sinter Temp.	Consolidation Method	Consolidation Temp.	ThO_2 Size Heat Treat	1400°F Roll. Can Mat'l	Starting Unit lbs.	Shipped lbs.
3514	0.015	1750°F	Roll	1850°F	2150°F	Mild Steel	100.0	37.0
3511	0.015	1750°F	Roll	1850°F	2150°F	Mild Steel	100.0	36.0
3509	0.040	1750°F	Roll	1850°F	2150°F	Mild Steel	100.0	43.7
3515	0.040	1750°F	Roll	1850°F	2150°F	Mild Steel	100.0	46.3
3517	0.020	1750°F	Roll	1850°F	2150°F	Mild Steel	100.0	33.5
3512	0.030	1750°F	Roll	1850°F	2150°F	Mild Steel	100.0	7.0
3513	0.030	1750°F	Roll	1850°F	2150°F	Mild Steel	100.0	26.3
3359	0.080	1750°F	Roll	1850°F	None	Mild Steel	100.0	36.8
3496	0.123	1750°F	Roll	1850°F	None	Mild Steel	100.0	15.2
3518	0.020	1750°F	Roll	1850°F	2150°F	Mild Steel	100.0	16.8
3622	0.030	1750°F	Roll	1850°F	2000°F	Al. Steel	100.0	53.2
3638	0.030	1750°F	Roll	1850°F	2000°F	Al. Steel	99.9	48.8
3639	0.030	1750°F	Roll	1850°F	2000°F	Al. Steel	100.0	43.5
3626	0.030	1750°F	Roll	1850°F	2000°F	Al. Steel	100.0	48.1
3455	0.080	1750°F	Roll	1850°F	None	Al. Steel	99.7	20.9
3629	0.020	1750°F	Roll	1850°F	2000°F	Al. Steel	100.0	18.1
3636	0.020 0.015	1750°F	Roll	1850°F	2000°F	Al. Steel	100.0	32.3
3628	0.030	1750°F	Roll	1850°F	2000°F	Al. Steel	100.0	32.7
3623	0.040	2050°F	Roll	2050°F	None	Al. Steel	99.9	56.7
3624	0.040	2150°F	Roll	2150°F	None	Al. Steel	99.9	46.8
3640	0.020 0.015	1750°F	Roll	1850°F	2000°F	Al. Steel	100.0	37.8
3630	0.020 0.015	1750°F	Roll	1850°F	2000°F	Al. Steel	100.0	34.9
3632	0.010	1750°F	Roll	1850°F	2000°F	Al. Steel	100.0	9.1
3634	0.010	1750°F	Roll	1850°F	2000°F	Al. Steel	100.0	22.5
3635	0.010	1750°F	Roll	1850°F	2000°F	Al. Steel	100.0	34.5
3637	0.010	1750°F	Roll	1850°F	2000°F	Al. Steel	100.0	5.5
3453	0.100	1750°F	Roll	1850°F	None	Al. Steel	99.6	26.3
3627	0.010	1750°F	Roll	1850°F	2000°F	Al. Steel	100.0	12.0
3520	0.010	1750°F	Roll	1850°F	2000°F	Al. Steel	150.0	18.7
3523	0.010	1750°F	Roll	1850°F	2000°F	Al. Steel	150.0	21.6
3526	0.010	1750°F	Roll	1850°F	2000°F	Al. Steel	150.0	39.5

TABLE 56 (CONT'D)

PRODUCTION HEATS OF TDNiCr AND PROCESSING HISTORY

Heat No.	Gauge cm.	Sinter Temp.	Consolidation Method	Consolidation Temp.	ThO_2 Size Heat Treat	760°C Roll. Can Mat'l.	Starting Unit kg.	Shipped kg.
3522	0.025	954°C	Roll	1010°C	1093°C	Al. Steel	68.04	1.68
3694	0.025	954°C	Roll	1010°C	None	Al. Steel	68.04	12.20
3525	0.025	954°C	Roll	1010°C	1093°C	Al. Steel	68.04	1.77
3519	0.038	954°C	Roll	1010°C	1093°C	Al. Steel	68.49	8.48
						TOTAL WEIGHT	2,839.5	820.6

TABLE 56 (CONT'D)

PRODUCTION HEATS OF TDNiCr AND PROCESSING HISTORY

Heat No.	Gauge in.	Sinter Temp.	Consolidation Method	Consolidation Temp.	ThO_2 Size Heat Treat	1400°F Roll. Can Mat'l	Starting Unit lbs.	Shipped lbs.
3522	0.010	1750°F	Roll	1850°F	2000°F	Al. Steel	150.0	3.7
3694	0.010	1750°F	Roll	1850°F	None	Al. Steel	150.0	26.9
3525	0.010	1750°F	Roll	1850°F	2000°F	Al. Steel	150.0	3.9
3519	0.015	1750°F	Roll	1850°F	2000°F	Al. Steel	151.0	18.7
						TOTAL WEIGHT	6,259.9	1,808.66

Generally speaking, product yields improve as product gauges increase because of less edge and end losses occurring as a result of fewer decanning and recanning operations. For this reason Heats 3321 through 3325 do not reflect realistic yield data as gauges produced varied greatly within each of these heats.

In order to determine true product yields of production sheet, those heats fabricated by the finalized process described in Section I-2-C of this report are considered to be the most representative, while the remaining heats processed prior to the thoria size control at the 2.54 cm.(1.0 in.) slab stage of processing were considered the least representative. Therefore, actual product yield versus gauge of the most representative heats are shown in Table 57.

The product yields of the five heats of 0.025 cm.(0.010 in.) sheet shown in Table 57 range from 9.1 percent to a high of 38.0 percent. Heats 3635 and 3637 were tension cold finish rolled while Heats 3627, 3634 and 3632 were all hand cold finish rolled. This same trend of low yield may be noted on earlier heats of 0.025 cm.(0.010 in.) sheet produced for the production requirements. These heats included 3387, 3382, 3416, 3419 and 3414 and were also hand rolled.

Pinching of the sheet during cold finishing is frequently encountered in hand rolling without tension. A heavily pinched sheet must then be scrapped or at least be trimmed to a smaller size causing a reduction in yield. This difficulty was overcome by tension rolling as indicated by Heats 3635 and 3637. Improved flatness and sheet shape were also achieved by this technique.

TABLE 57

PRODUCT YIELD VERSUS GAUGE FOR FINALIZED PROCESS FABRICATED PRODUCTION TDNiCr SHEET

Heat No.	Gauge cm.	Gauge in.	Product Yield %
3627	0.025	0.010	12.0
3637	0.025	0.010	32.7
3635	0.025	0.010	38.0
3634	0.025	0.010	22.5
3632	0.025	0.010	9.1
3514	0.038	0.015	37.0
3511	0.038	0.015	36.0
3636	0.038 0.051	0.015 0.020	32.3
3640	0.038 0.051	0.015 0.020	37.8
3630	0.038 0.051	0.015 0.020	34.9
3493	0.051	0.020	38.5
3510	0.051	0.020	38.0
3516	0.051	0.020	35.6
3499	0.051	0.020	38.2
3494	0.051	0.020	36.3
3517	0.051	0.020	33.5
3518	0.051	0.020	16.1
3629	0.051	0.020	18.1
3508	0.076	0.030	38.4
3501	0.076	0.030	42.4
3512	0.076	0.030	7.0
3513	0.076	0.030	26.3
3622	0.076	0.030	53.2
3638	0.076	0.030	48.0
3639	0.076	0.030	43.5
3626	0.076	0.030	48.1
3628	0.076	0.030	32.7

During scale-up studies to longer sheets, this procedure was found to be mandatory to produce cold finished 0.025 cm.(0.010 in.) sheet.

Again referring to Table 57, it may be noted that yields from thirteen heats of TDNiCr sheet at gauges of either 0.038 cm. (0.015 in.) or 0.051 cm.(0.020 in.) ranged between 32.3 and 38.5 percent with the exception of Heat 3518 and Heat 3629 which were 16.1 and 18.1 percent respectively. The extremely low yield encountered on Heat 3518 was due to an exceptionally large loss during conditioning at the 2.54 cm.(1.0 in.) slab stage of processing. Excessive edge cracking and surface tearing resulted from can breakage during roll consolidation and subsequent hot rolling. On the other hand, some sheets of Heat 3629 did not satisfy bend requirements and were rejected. No assignable cause for this difficulty could be established.

Finally, as indicated in Table 57, product yields for the 0.076 cm.(0.030 in.) production sheet were found to range between 32.7 and 53.2 percent with the exception of Heats 3512 and 3513 which were 7.0 and 26.3 percent respectively. The yields on these two heats were low due to poor stress rupture properties. Both of these heats had been subjected to a 1177°C(2150°F) heat treat at the 2.54 cm.(1.0 in.) slab size, and are believed to have been marginal in that the thoria size was larger than anticipated.

Summarizing, the data shown in Table 57 indicate that 0.025 cm.(0.010 in.) sheet produced by the cold rolled annealed finish technique yields an average of 35.4 percent finished

product, based on the two heats which were tension cold finished. Representative heats of 0.038 to 0.051 cm.(0.015 to 0.020 in.) sheet yields an average of 36.1 percent product and 0.076 cm. (0.030 in.) sheet yield a 43.8 percent product. All of these data were based upon a 45.36 kg.(100 lb.) starting size unit.

Also, it may be noted on Table 57 that the gauges supplied for the production requirement of this program ranged from 0.025 cm. (0.010 in.) sheet up to 0.699 cm.(0.275 in.) plate. Since Fansteel Product Specifications S-TC-S-01-R-1, December 1, 1969 and S-DMM-S-01-R-0, January 1, 1969 cover sheet up to 0.191 cm.(0.075 in.) in thickness, sheet and plate being thicker were certified for chemistry only.

It should, however, be pointed out that all nominal 0.635 cm. (0.250 in.) plate was found to require a 1316°C(2400°F) heat treatment to achieve full recrystallization rather than the usual 1177°C (2150°F) heat treatment utilized for standard gauge sheet processing.

Mechanical properties and/or chemical analysis of all production sheet and/or plate shipped during Part I are summarized in Table 58. Discussion of these mechanical properties relative to the reproducibility property evaluation was included in Section I-2-C of this report.

Chemical analysis data representing the fifty-nine heats shown in Table 58 indicate a range of thoria contents from a low of 1.90 percent to a high of 2.27 percent. As compared to a specification goal of 1.80-2.60 percent presented in Exhibit A of the contract, these results appear very favorable and the goal quite realistic.

TABLE 58

MECHANICAL PROPERTIES AND CHEMICAL ANALYSIS OF PRODUCTION SHEET

Heat No.	Gauge cm.	Room Temperature UTS MN/m^2	Room Temperature YS MN/m^2	Room Temperature Elong. % cm.	1093°C UTS MN/m^2	1093°C YS MN/m^2	1093°C Elong. % cm.	Stress Rupture Hrs. @ 1093°C 31.0 MN/m^2	Stress Rupture Hrs. @ 1093°C 37.9 MN/m^2	Chemistry Weight % ThO_2	Cr	C	S
3321	0.051	815.8 821.3	607.0 569.1	27.5 20.0	111.6 126.8	97.1 126.8	6.5 5.0		>20	2.02	19.40	.0243	.0048
	0.203									2.02	19.40	.0243	.0048
3322	0.025	780.6	536.7	20.0	99.2	99.2	3.0	>20*		2.02	19.58	.0237	.0054
	0.038	814.4	569.8	21.0	115.1	115.1	5.0	>20*		2.02	19.58	.0237	.0054
	0.102	795.1	516.1	22.5	113.0	105.4	6.0		>20	2.02	19.58	.0237	.0054
	0.152	824.7	552.6	23.5	127.5	113.0	10.0		>20	2.02	19.58	.0237	.0054
3323	0.038	814.4	567.0	15.0	104.0	104.0	3.0	>20*		2.02	19.57	.0129	.0057
	0.064	757.9	542.9	12.5	117.1	117.1	6.0		>20	2.02	19.57	.0129	.0057
3324	0.025	881.2	613.9	22.5	102.7	99.2	6.0						
	0.025	815.8	554.6	20.5	109.6	106.8	2.5	>20*		1.98	19.39	.0245	.0064
	0.038	890.1	613.9	22.5	102.7	99.2	6.0	>20*		1.98	19.39	.0245	.0064
	0.127	832.3	565.7	24.2	130.2	111.6	2.5		>20	1.98	19.39	.0245	.0064
3325	0.152	855.4	613.2	24.0	126.8	107.5	5.5		>20	1.99	19.27	.0136	.0054
	0.635									1.99	19.27	.0136	.0054
3387	0.025	777.9	604.9	23.0	100.6	100.6	4.5	>20*		2.25	18.40	.0045	.0035
3382	0.025	750.3	533.3	20.5	141.9	141.9	6.0	>20*		2.27	19.85	.0348	.0047

TABLE 58

MECHANICAL PROPERTIES AND CHEMICAL ANALYSIS OF PRODUCTION SHEET

Heat No.	Gauge in.	Room Temperature UTS ksi	Room Temperature YS ksi	Room Temperature Elong. %-in.	2000°F UTS ksi	2000°F YS ksi	2000°F Elong. %-in.	Stress Rupture Hrs. @ 2000°F 4500 psi	Stress Rupture Hrs. @ 2000°F 5500 psi	Chemistry Weight % ThO_2	Cr	C	S
3321	0.020	118.4	88.1	27.5	16.2	14.1	6.5						
		119.2	82.6	20.0	18.4	18.4	5.0		>20	2.02	19.40	.0243	.0048
	0.080									2.02	19.40	.0243	.0048
3322	0.010	113.3	77.9	20.0	14.4	14.4	3.0	>20*					
	0.015	118.2	82.7	21.0	16.7	16.7	5.0	>20*		2.02	19.58	.0237	.0054
	0.040	115.4	74.9	22.5	16.4	15.3	6.0		>20	2.02	19.58	.0237	.0054
	0.060	119.7	80.2	23.5	18.5	16.4	10.0		>20	2.02	19.58	.0237	.0054
3323	0.015	118.2	82.3	15.0	15.1	15.1	3.0	>20*		2.02	19.57	.0129	.0057
	0.025	110.0	78.8	12.5	17.0	17.0	6.0		>20	2.02	19.57	.0129	.0057
3324	0.010	127.9	89.1	22.5	14.9	14.4	6.0						
		118.4	80.5	20.5	15.9	15.5	2.5	>20*		1.98	19.39	.0245	.0064
	0.015	129.2	89.1	22.5	14.9	14.4	6.0	>20*		1.98	19.39	.0245	.0064
	0.050	120.8	82.1	24.2	18.9	16.2	2.5		>20	1.98	19.39	.0245	.0064
3325	0.060	128.5	89.0	24.0	18.4	15.6	5.5		>20	1.99	19.27	.0136	.0054
	0.250									1.99	19.27	.0136	.0054
3387	0.010	112.9	87.8	23.0	14.6	14.6	4.5	>20*		2.25	18.40	.0045	.0035
3382	0.010	108.9	77.4	20.5	20.6	20.6	6.0	>20*		2.27	19.85	.0348	.0047

TABLE 58 (CONT'D)

MECHANICAL PROPERTIES AND CHEMICAL ANALYSIS OF PRODUCTION SHEET

Heat No.	Gauge cm.	Room Temperature UTS MN/m^2	Room Temperature YS MN/m^2	Room Temperature Elong. % cm.	1093°C UTS MN/m^2	1093°C YS MN/m^2	1093°C Elong. % cm.	Stress Rupture Hrs. @1093°C 31.0 MN/m^2	Stress Rupture Hrs. @1093°C 37.9 MN/m^2	Chemistry Weight % ThO_2	Cr	C	S
3416	0.025	818.5	535.3	18.5	103.4	103.4	4.0	>20*		2.11	18.85	.0058	.0037
3384	0.635	846.8	745.5	12.5	116.4	113.7	6.0			1.90	19.66	.0276	.0058
3361	0.038	791.0	539.5	23.0	113.7	113.7	5.0	>20*		2.31	19.35	.0076	.0030
3472	0.699	895.7	707.6	17.0	82.7	79.2	4.0			2.13	20.21	.0351	.0022
3419	0.025	701.4	505.0	20.6	93.0	89.6	3.0	>20*		2.02	19.76	.0250	.0038
3414	0.025	749.6	536.7	21.0	95.8	95.8	2.5	>20*		2.23	20.04	.0104	.0033
3435	0.025	704.2	514.7	17.5	104.0	104.0	4.0	>20*		2.12	19.96	.0390	.0025
3436	0.025	835.8	620.1	20.0	75.1	75.1	4.0	>20*		2.13	19.98	.0402	.0028
3493	0.051	834.4	554.6	22.0	122.0	122.0	3.0		>20	2.08	19.34	.0346	.0028
3510	0.051	830.9	571.2	22.5	126.1	124.7	3.0		>20	2.08	18.95	.0246	.0028
3507	0.051	835.1	556.7	23.0	126.8	126.8	4.0		>20	2.08	20.09	.0122	.0029
	0.102	799.2	525.7	24.0	122.0	122.0	4.0		>20	2.08	20.09	.0122	.0029
3473	0.025	871.6	640.1	20.0	114.4	114.4	5.0	>20*		2.09	19.44	.0186	.0025
	0.102	871.6	571.9	22.0	126.8	124.7	2.8		>20	2.09	19.44	.0186	.0025
3516	0.051	821.9	586.3	15.0	128.2	121.3	3.0		>20	2.00	19.63	.0134	.0022
3499	0.051	915.7	531.9	22.5	124.0	124.0	4.5		>20	2.15	20.08	.0262	.0017

TABLE 58 (CONT'D)

MECHANICAL PROPERTIES AND CHEMICAL ANALYSIS OF PRODUCTION SHEET

Heat No.	Gauge in.	Room Temperature UTS ksi	Room Temperature YS ksi	Room Temperature Elong. %-in.	2000°F YTS ksi	2000°F YS ksi	2000°F Elong. %-in.	Stress Rupture Hrs. @ 2000°F 4500 psi	Stress Rupture Hrs. @ 2000°F 5500 psi	Chemistry Weight % ThO_2	Chemistry Weight % Cr	Chemistry Weight % C	Chemistry Weight % S
3416	0.010	118.8	77.7	18.5	15.0	15.0	4.0	>20*		2.11	18.85	.0058	.0037
3384	0.250	122.9	108.2	12.5	16.9	16.5	6.0			1.90	19.66	.0276	.0058
3361	0.015	114.8	78.3	23.0	16.5	16.5	5.0	>20*		2.31	19.35	.0076	.0030
3472	0.275	130.0	102.7	17.0	12.0	11.5	4.0			2.13	20.21	.0351	.0022
3419	0.010	101.8	73.3	20.6	13.5	13.0	3.0	>20*		2.02	19.76	.0250	.0038
3414	0.010	108.8	77.9	21.9	13.9	13.9	2.5	>20*		2.23	20.04	.0104	.0033
3435	0.010	102.2	74.7	17.5	15.1	15.1	4.0	>20*		2.12	19.96	.0390	.0025
3436	0.010	121.3	90.0	20.0	10.9	10.9	4.0	>20*		2.13	19.98	.0402	.0028
3493	0.020	121.1	80.5	22.0	17.7	17.7	3.0		>20	2.08	19.34	.0346	.0028
3510	0.020	120.6	82.9	22.5	18.3	18.1	3.0		>20	2.08	18.95	.0246	.0028
3507	0.020	121.2	80.8	23.0	18.4	18.4	4.0		>20	2.08	20.09	.0122	.0029
	0.040	116.0	76.3	24.0	17.7	17.7	4.0		>20	2.08	20.09	.0122	.0029
3473	0.010	126.5	92.9	20.0	16.6	16.6	5.0	>20*		2.09	19.44	.0186	.0025
	0.040	126.5	83.0	22.0	18.4	18.1	2.8		>20	2.09	19.44	.0186	.0025
3516	0.020	119.3	85.1	15.0	18.6	17.6	3.0		>20	2.00	19.63	.0134	.0022
3499	0.020	132.9	77.2	22.5	18.0	18.0	4.5		>20	2.15	20.08	.0262	.0017

TABLE 58 (CONT'D)

MECHANICAL PROPERTIES AND CHEMICAL ANALYSIS OF PRODUCTION SHEET

Heat No.	Gauge cm.	Room Temperature UTS MN/m^2	Room Temperature YS MN/m^2	Room Temperature Elong. % cm.	1093°C UTS MN/m^2	1093°C YS MN/m^2	1093°C Elong. % cm.	Stress Rupture Hrs. @1093°C 31.0 MN/m^2	Stress Rupture Hrs. @1093°C 37.9 MN/m^2	Chemistry Weight % ThO_2	Chemistry Weight % Cr	Chemistry Weight % C	Chemistry Weight % S
3494	0.051	817.8	545.0	025.0	114.4	102.7	2.8		>20	2.05	19.60	.0052	.0024
3508	0.076	824.0	520.9	022.5	143.3	141.9	5.0		>20	2.16	19.93	.0154	.0015
3501	0.076	802.7	523.6	018.0	139.2	137.1	3.0		>20	2.07	20.08	.0160	.0035
3514	0.038	824.0	583.6	025.0	103.4	103.4	2.6	>20*		1.98	19.20	.0156	.0026
3511	0.038	786.8	508.5	023.0	99.9	99.9	1.7	>20*		2.07	20.06	.0184	.0028
3509	0.102	864.7	587.0	023.7	123.3	122.0	3.2		>20	1.98	19.60	.0114	.0036
3515	0.102	799.2	533.9	026.3	124.0	124.0	3.0		>20	1.95	19.65	.0146	.0025
3517	0.051	760.7	520.9	022.5	120.6	120.6	5.0		>20	2.00	19.63	.0134	.0022
3512	0.076	842.6	563.6	025.0	111.6	107.5	4.3		>20	1.98	19.65	.0134	.0028
3513	0.076	818.5	545.7	025.0	118.5	118.5	3.0		>20	1.96	19.77	.0126	.0022
3359	0.203	880.5	633.2	022.5	160.5	140.6	2.3		>20	2.25	19.93	.0300	.0035
3496	0.312	912.2	680.0	023.3	106.8	101.3	2.6		>20	2.18	19.78	.0372	.0024
3518	0.051	828.2	554.0	019.6	122.6	116.4	2.5		>20	1.99	19.89	.0074	.0023
3622	0.076	861.3	550.5	021.2	124.0	124.0	3.0		>20	2.13	19.73	.0104	.0024
3638	0.076	826.1	537.4	020.0	132.9	132.9	2.5		>20	2.20	19.91	.0272	.0029
3639	0.076	852.9	547.0	020.5	139.2	139.2	2.5		>20	2.11	19.25	.0190	.0015

TABLE 58 (CONT'D)

MECHANICAL PROPERTIES AND CHEMICAL ANALYSIS OF PRODUCTION SHEET

Heat No.	Gauge in.	Room Temperature UTS ksi	Room Temperature YS ksi	Room Temperature Elong. %-in.	2000°F UTS ksi	2000°F YS ksi	2000°F Elong. %-in.	Stress Rupture Hrs. @ 2000°F 4500 psi	Stress Rupture Hrs. @ 2000°F 5500 psi	Chemistry Weight % ThO_2	Cr	C	S
3494	0.020	118.7	79.1	25.0	16.6	14.9	2.8		>20	2.05	19.60	.0052	.0024
3508	0.030	119.6	75.6	22.5	20.8	20.6	5.0		>20	2.16	19.93	.0154	.0015
3501	0.030	116.5	76.0	18.0	20.2	19.9	3.0		>20	2.07	20.08	.0160	.0035
3514	0.015	119.6	84.7	25.0	15.0	15.0	2.6	>20*		1.98	19.20	.0156	.0026
3511	0.015	114.2	73.8	23.0	14.5	14.5	1.7	>20*		2.07	20.06	.0184	.0028
3509	0.040	125.5	85.2	23.7	17.9	17.7	3.2		>20	1.98	19.60	.0114	.0036
3515	0.040	116.0	77.5	26.3	18.0	18.0	3.0		>20	1.95	19.65	.0146	.0025
3517	0.020	110.4	75.6	22.5	17.5	17.5	5.0		>20	2.00	19.63	.0134	.0022
3512	0.030	122.3	81.8	25.0	16.2	15.6	4.3		>20	1.98	19.65	.0134	.0028
3513	0.030	118.8	79.2	25.0	17.2	17.2	3.0		>20	1.96	19.77	.0126	.0022
3359	0.080	127.8	91.9	22.5	23.3	20.4	2.3		>20	2.25	19.93	.0300	.0035
3496	0.123	132.4	98.7	23.3	15.5	14.7	2.6		>20	2.18	19.78	.0372	.0024
3518	0.020	120.2	80.4	19.6	17.8	16.9	2.5		>20	1.99	19.89	.0074	.0023
3622	0.030	125.0	79.9	21.2	18.0	18.0	3.0		>20	2.13	19.73	.0104	.0024
3638	0.030	119.9	78.0	20.0	19.3	19.3	2.5		>20	2.20	19.91	.0272	.0029
3639	0.030	123.8	79.4	20.5	20.2	20.2	2.5		>20	2.11	19.25	.0190	.0015

TABLE 58 (CONT'D)

MECHANICAL PROPERTIES AND CHEMICAL ANALYSIS OF PRODUCTION SHEET

Heat No.	Gauge cm.	Room Temperature UTS MN/m^2	Room Temperature YS MN/m^2	Room Temperature Elong. % cm.	1093°C UTS MN/m^2	1093°C YS MN/m^2	1093°C Elong. % cm.	Stress Rupture Hrs. @ 1093°C 31.0 MN/m^2	Stress Rupture Hrs. @ 1093°C 37.9 MN/m^2	Chemistry Weight % ThO_2	Cr	C	S
3626	0.076	839.9	543.6	22.3	124.0	124.0	2.5		>20	2.17	19.73	.0328	.0030
3455	0.203									2.17	18.66	.0418	.0023
3629	0.051	821.9	593.9	25.0	149.5	149.5	2.5		>20	2.18	19.18	.0256	.0033
3636	0.051	815.8	578.8	19.0	136.4	136.4	2.0		>20	2.17	20.16	.0214	.0021
	0.038	828.2	576.0	19.0	141.2	141.2	2.0	>20		2.17	20.16	.0214	.0021
3628	0.076	876.4	604.9	20.8	128.8	128.8	2.5		>20	2.16	19.57	.0252	.0047
3623	0.102	846.8	567.0	20.5	141.2	141.2	2.5		>20	2.10	19.40	.0162	.0021
3624	0.102	809.6	571.9	22.5	132.3	132.3	2.5						
		791.7	541.6	22.5	121.9	117.1	5.0		>20	2.12	19.42	.0073	.0026
3640	0.051	775.1	530.5	22.5	141.9	141.9	3.5		>20	2.11	19.65	.0218	.0018
	0.038	830.9	578.8	17.5	124.0	124.0	2.0		>20	2.11	19.65	.0218	.0018
3630	0.051	868.8	583.6	20.3	143.3	142,6	5.0		>20	2.19	19.47	.0224	.0025
	0.038	850.9	545.7	17.5	139.2	138.5	3.0			2.19	19.47	.0224	.0025
3632	0.025	763.4	591.9	19.6	118.5	118.5	3.0						
		810.3	599.4	17.5	124.0	124.0	2.0	>20		2.17	19.61	.0364	.0015
3634	0.025	810.9	671.0	18.0	139.2	139.2	4.0						
		900.5	746.2	16.9	125.4	125.4	2.5	>20		2.15	19.87	.0242	.0020

TABLE 58 (CONT'D)

MECHANICAL PROPERTIES AND CHEMICAL ANALYSIS OF PRODUCTION SHEET

Heat No.	Gauge in.	Room Temperature UTS ksi	Room Temperature YS ksi	Room Temperature Elong. %-in.	2000°F UTS ksi	2000°F YS ksi	2000°F Elong. %-in.	Stress Rupture Hrs. @2000°F 4500 psi	Stress Rupture Hrs. @2000°F 5500 psi	Chemistry Weight % ThO_2	Chemistry Weight % Cr	Chemistry Weight % C	Chemistry Weight % S
3626	0.030	121.9	78.9	22.3	18.0	18.0	2.5		>20	2.17	19.73	.0328	.0030
3455	0.080									2.17	18.66	.0418	.0023
3629	0.020	119.3	86.2	25.0	21.7	21.7	2.5		>20	2.18	19.18	.0256	.0033
3636	0.020	118.4	84.0	19.0	19.8	19.8	2.0		>20	2.17	20.16	.0214	.0021
	0.015	120.2	83.6	19.0	20.5	20.5	2.0	>20		2.17	20.16	.0214	.0021
3628	0.030	127.2	87.8	20.8	18.7	18.7	2.5		>20	2.16	19.57	.0252	.0047
3623	0.040	122.9	82.3	20.5	20.5	20.5	2.5		>20	2.10	19.40	.0162	.0021
3624	0.040	117.5	83.0	22.5	19.2	19.2	2.5						
		114.9	78.6	22.5	17.7	17.0	5.0		>20	2.12	19.42	.0073	.0026
3640	0.020	112.5	77.0	22.5	20.6	20.6	3.5		>20	2.11	19.65	.0218	.0018
	0.015	120.6	84.0	17.5	18.0	18.0	2.0		>20	2.11	19.65	.0218	.0018
3630	0.020	126.1	84.7	20.3	20.8	20.7	5.0		>20	2.19	19.47	.0224	.0025
	0.015	123.5	79.2	17.5	20.2	20.1	3.0			3.19	19.47	.0224	.0025
3632	0.010	110.8	85.9	19.6	17.2	17.2	3.0						
		117.6	87.0	17.5	18.0	18.0	2.0	>20		2.17	19.61	.0364	.0015
3634	0.010	117.7	97.4	18.0	20.2	20.2	4.0						
		130.7	108.3	16.9	18.2	18.2	2.5	>20		2.15	19.87	.0242	.0020

TABLE 58 (CONT'D)

MECHANICAL PROPERTIES AND CHEMICAL ANALYSIS OF PRODUCTION SHEET

Heat No.	Gauge cm.	Room Temperature UTS MN/m^2	YS MN/m^2	Elong. % cm.	1093°C UTS MN/m^2	YS MN/m^2	Elong. % cm.	Stress Rupture Hrs. @ 1093°C 31.0 MN/m^2	37.9 MN/m^2	Chemistry Weight % ThO_2	Cr	C	S
3635	0.025	817.2	553.3	20.8	130.9	130.9	1.2	>20		2.12	19.92	.0204	.0023
3637	0.025	866.0	587.0	20.5	140.6	140.6	2.0	>20		2.14	19.80	.0194	.0019
3453	0.254									2.18	18.54	.0286	.0028
3627	0.025	842.6	544.9	20.0	130.2	130.2	2.0	>20		2.18	19.54	.0354	.0030
3520	0.025	757.9	607.7	13.8	119.2	119.2	2.5						
		731.0	551.9	20.0	75.1	75.1	2.5	>20		2.06	20.02	.0272	.0044
3523	0.025	770.9	655.9	19.6	108.1	108.1	3.0	>20		2.00	19.99	.0100	.0043
3526	0.025	691.8	465.1	20.0	84.1	82.7	1.2	>20		2.14	19.74	.0184	.0049
3522	0.025	775.8	531.2	15.5	129.5	129.5	1.6	>20		2.08	20.01	.0120	.0053
3694	0.025	733.1	509.2	20.0	93.7	93.7	1.0	>20		2.13	19.88	.0158	.0046
3525	0.025	689.0	464.4	20.9	108.2	108.2	1.7	>20		2.17	18.66	.0186	.0035
3519	0.038	789.6	520.2	20.0	101.3	101.3	4.5	>20		2.04	19.66	.0122	.0046

*Tested at 27.6 MN/m^2

TABLE 58 (CONT'D)

MECHANICAL PROPERTIES AND CHEMICAL ANALYSIS OF PRODUCTION SHEET

Heat No.	Gauge in.	Room Temperature UTS ksi	YS ksi	Elong. %-in.	2000°F UTS ksi	YS ksi	Elong. %-in.	Stress Rupture Hrs. @ 2000°F 4500 psi	5500 psi	Chemistry Weight % ThO_2	Cr	C	S
3635	0.010	118.6	80.3	20.8	19.0	19.0	1.2	<20		2.12	19.92	.0204	.0023
3637	0.010	125.7	85.2	20.5	20.4	20.4	2.0	<20		2.14	19.80	.0194	.0019
3453	0.100									2.18	18.54	.0286	.0028
3627	0.010	122.3	79.1	20.0	18.9	18.9	2.0	<20		2.18	19.54	.0354	.0030
3520	0.010	110.0	88.2	13.8	17.3	17.3	2.5						
		106.1	80.1	20.0	10.9	10.9	2.5	<20		2.06	20.02	.0272	.0044
3523	0.010	111.9	95.2	19.6	15.7	15.7	3.0	<20		2.00	19.99	.0100	.0043
3526	0.010	100.4	67.5	20.0	12.2	12.0	1.2	<20		2.14	19.74	.0184	.0049
3522	0.010	112.6	77.1	15.5	18.8	18.8	1.6	<20		2.08	20.01	.0120	.0053
3694	0.010	106.4	73.9	20.0	13.6	13.6	1.0	<20		2.13	19.88	.0158	.0046
3525	0.010	100.0	67.4	20.9	15.7	15.7	1.7	<20		2.17	18.66	.0186	.0035
3519	0.015	114.6	75.5	20.0	14.7	14.7	4.5	<20		2.04	19.96	.0122	.0046

*Tested at 4000 psi.

The chromium contents were found to range from 18.40 to 20.21 percent in comparison to a specification goal of 19.00 to 21.00 percent. While the actual range experienced was tighter than the range specified by the goal, a shift downward in chromium content was encountered. Since this shift did not appear to have any detrimental effects upon mechanical properties as discussed in Section I-2-C in this report, it is recommended that the proposed goal chromium content be established at 18.50 to 20.50 percent.

Carbon contents in excess of 0.03 percent specified as a goal content were experienced during the fabrication of production TDNiCr sheet from the fifty-nine heats shown in Table 58. Since these values did not appear to have any adverse effect upon mechanical properties of the material evaluated, a more realistic goal than 0.03 percent was believed to be 0.05 percent maximum carbon content.

Sulfur content of a 0.01 percent maximum content was easily achieved and appears, also, to be a realistic goal figure.

Again referring to Table 56, "Production Heats of TDNiCr and Processing History", it may be noted that a total of 820.4 kg.(1,808.6 lbs.) of TDNiCr sheet and plate were shipped to NASA designated locations through the end of Part I of this contract. Individual sheet and plate inventories for the eight shipments involved are included as Appendix D, TDNiCr Sheet Shipments.

II - TDNiCr SHEET PROCESS DEVELOPMENT

1. Program Requirements

A series of process studies have been designed to expand the gauge and size capabilities and to improve the product quality. The following requirements were established for these studies.

- An alternate process route shall be developed for 0.025-0.102 cm. (0.010-0.040 in.) gauge sheet to provide improvements in high temperature ductility and gauge control.
- An interim process shall be developed for the production of foil, <0.025 cm. (<0.010 in.).
- Rolling and finishing procedures shall be developed to improve gauge control, flatness, and surface finish.
- The size capability of the processes and equipment shall be extended to produce the following standard sizes:

  0.025-0.102 cm. (0.010-0.040 in.) gauge sheet
  61 cm. (24 in.) wide x 152 cm. (60 in.) long
  <0.025 cm. (<0.010 in.) gauge foil
  30 cm. (12 in.) wide x 122 cm. (48 in.) long

2. Alternate Process Study

The effort in this portion of the contract was redirected in January 1971.

Improvements in ductility had been obtained during Task I of this program for all gauges, and the need for a special process study to improve ductility was minimized.

As a result, the following program outline was implemented:

- No alternate process studies were conducted for 0.051-0.102 cm. (0.020-0.040 in.) gauge sheet.
- Alternate process studies for 0.025-0.051 cm. (0.010-0.020 in.) sheet were minimized with principal efforts directed to the use of cold rolling to augment the finishing practice.
- Alternate process studies were included as part of the foil program.

Prior to the redirection of this phase of the program, however, certain studies were carried out to determine the effects of both warm and cold rolling of recrystallized TDNiCr sheet upon mechanical properties.

a. Rolling Studies on Recrystallized TDNiCr Sheet

Two recrystallized sheets, one at 0.056 cm. (0.022 in.) from Heat 3436 and one at 0.051 cm. (0.020 in.) from Heat 3468 were warm rolled at 760°C(1400°F) to various gauges and properties obtained as a function of percent reduction. Warm work of up to 46 percent reduction was insufficient to effect recrystallization after a 2 hour heat treatment at 1177°C (2150°F) as evidenced by room temperature mechanical properties, bend radii and diamond pyramid hardness tests shown in Table 59. No consistent effect was observed on elevated temperature properties. All specimens exceeded 20 hours at a 27.6 MN/m^2 (4000 psi) load at 1093°C(2000°F) for stress rupture evaluation.

Metallographical examination revealed no noticeable change in grain size, although some grain elongation in the longitudinal specimens was observed.

Warm rolling recrystallized TDNiCr appears to cause a loss of room temperature ductility, therefore no further work was planned for this approach.

One recrystallized sheet at 0.079 cm. (0.031 in.) gauge from Heat 3383 having an abnormally large grained structure was subjected to various cold rolling reductions in an effort to improve bend properties through the establishment of a finer grained structure. After cold reductions of 18, 22, 33, 43, and 53 percent respectively, samples at each reduction were heat treated at 1177°C(2150°F) for 2 hours. Recrystallization however did not occur. Metallographic evaluation showed no apparent change in grain size. Room temperature strength and minimum bend radii increased linearly with percent reduction as shown in Table 60. As in the warm rolling study, no consistent effect was observed on elevated temperature strength. All gauge samples exceeded 20 hours during a stress rupture test at a 34.5 MN/m^2(5500 psi) load at 1093°C(2000°F).

These data indicate that recrystallization is required to obtain room temperature ductility. Further study on this approach was continued on the TDNiCr Foil Study.

TABLE 59

EFFECT OF WARM WORK ON RECRYSTALLIZED TDNiCr SHEET

Heat No.	Gauge cm.	Room Temperature % Reduction	UTS MN/m^2	YS MN/m^2	Elong. % cm.	1093°C UTS MN/m^2	YS MN/m^2	Elong. % cm.	Min. Bend Radii*	DPH**
3436	0.056	0	744.1	504.3	25.0	112.3	112.3	6.0	4.1	290
3436	0.051	9	762.7	642.1	17.5	121.9	121.9	1.8	5.9	292
3436	0.043	23	760.7	659.4	17.0	106.8	106.8	2.9	7.2	309
3436	0.038	32	786.8	697.3	17.5	104.0	104.0	2.8	7.1	315
3436	0.030	46	845.4	761.3	13.0	132.3	132.3	2.5	6.0	336
3468	0.102	0	784.8	515.4	24.0	138.5	137.1	5.0	6.5	260
3468	0.038	25	790.3	666.9	20.0	121.3	121.3	3.2	7.8	298
3468	0.030	40	821.9	702.1	20.0	144.7	144.7	3.0	7.1	320

*Bend Test Specimens polished through 400 grit paper.
Examined for cracks at 1X.

**300 gram load at 20X

TABLE 59

EFFECT OF WARM WORK ON RECRYSTALLIZED TDNiCr SHEET

Heat No.	Gauge in.	% Reduction	Room Temperature UTS ksi	Room Temperature YS ksi	Room Temperature Elong. %-in.	2000°F UTS ksi	2000°F YS ksi	2000°F Elong. %-in.	Min. Bend Radii*	DPH**
3436	0.022	0	108.0	73.2	25.0	16.3	16.3	6.0	4.1	290
3436	0.020	9	110.7	93.2	17.5	17.7	17.7	1.8	5.9	292
3436	0.017	23	110.4	95.7	17.0	15.5	15.5	2.9	7.2	309
3436	0.015	32	114.2	101.2	17.5	15.1	15.1	2.8	7.1	315
3436	0.012	46	122.7	110.5	13.0	19.2	19.2	2.5	6.0	336
3468	0.020	0	113.9	74.8	24.0	20.1	19.9	5.0	6.5	260
3468	0.015	25	114.7	96.8	20.0	17.6	17.6	3.2	7.8	298
3468	0.012	40	119.3	101.9	20.0	21.0	21.0	3.0	7.1	320

* Bend Test Specimens polished through 400 grit paper. Examined for cracks at 1X.

** 300 gram load at 20X.

TABLE 60

EFFECT OF COLD WORK ON RECRYSTALLIZED TDNiCr SHEET

Heat No.	Gauge cm.	% Reduction	Room Temperature UTS MN/m^2	Room Temperature YS MN/m^2	Room Temperature Elong. % cm.	1093°C UTS MN/m^2	1093°C YS MN/m^2	1093°C Elong. % cm.	Min. Bend* Radii
3383	0.079	0	759.9	516.8	27.5	137.8	130.2	6.5	5.0
3383	0.066	18	815.8	761.3	19.5	110.2	110.2	5.5	6.0
3383	0.061	22	821.3	707.6	19.5	120.6	120.6	5.5	9.0
3383	0.053	33	886.7	809.6	18.0	128.8	128.8	5.5	12.0
3383	0.046	43	922.6	866.8	17.5	131.6	131.6	5.5	12.0
3383	0.038	53	1006.6	841.9	17.5	120.6	115.8	6.0	14.0

*Bend Test Specimens polished through 400 grit paper.
Examined at 1X for cracks.

TABLE 60

EFFECT OF COLD WORK ON RECRYSTALLIZED TDNiCr SHEET

Heat No.	Gauge in.	% Reduction	Room Temperature UTS ksi	Room Temperature YS ksi	Room Temperature Elong. %-in.	2000°F UTS ksi	2000°F YS ksi	2000°F Elong. %-in.	Min. Bend* Radii
3383	0.031	0	110.3	75.0	27.5	20.0	18.9	6.5	5.0
3383	0.026	18	118.4	110.5	19.5	16.0	16.0	5.5	6.0
3383	0.024	22	119.2	102.7	19.5	17.5	17.5	5.5	9.0
3383	0.021	33	128.7	117.5	18.0	18.7	18.7	5.5	12.0
3383	0.018	43	133.9	125.8	17.5	19.1	19.1	5.5	12.0
3383	0.015	53	146.1	122.2	17.5	17.5	16.8	6.0	14.0

* Bend Test Specimens polished through 400 grit paper.
Examined at 1X for cracks.

3. TDNiCr Foil

The studies on foil processing were subdivided into two categories:

- An interim process was to be developed to produce 45.72 x 121.92 cm. (18 x 48 in.) foil at gauges from 0.025 cm. (0.010 in.) down to the limit of the rolling equipment at Baltimore. At a later date, the width requirement would be scaled to 60.96 cm. (24 in.) either at the Baltimore Plant or at a toll facility.
- An interim process was to be developed to produce 30.48 x 121.92 cm. (12 x 48 in.) foil at gauges of 0.0051-0.0127 cm. (0.002-0.005 in.). Final rolling is planned for the Sendzimir Rolling Mill at the Fansteel North Chicago Plant or at a toll facility.

A portion of material from a series of seven 45.36 kg. (100 lb.) units that were fabricated to 0.051 cm. (0.020 in.) sheet by conventional processing techniques was isothermally rolled to 0.025 cm. (0.010 in.) in preparation for this phase of the program. All of this material was fabricated from heats containing fine ThO_2, 12 mμ at the 2.54 cm. (1.0 in.) slab stage. Larger ThO_2 size material (greater than 15 mμ) was also utilized for foil rolling.

a. Baltimore Foil Rolling

Two types of rolling were initiated at the Baltimore facility for the rolling of foil. These consisted of warm pack rolling of 0.025 cm. (0.010 in.) unrecrystallized TDNiCr sheet on a two high United Mill having rolls 66.04 cm. (26 in.)

in diameter by 91.44 cm. (36 in.) wide and cold tension rolling of recrystallized 0.025 cm. (0.010 in.) TDNiCr sheet on the Schloemann Mill employing a single cluster roll configuration.

(1.) Warm Rolling

The technique employed for warm pack rolling of TDNiCr sheet less than 0.025 cm. (0.010 in.) thickness is similar to that employed for rolling of TDNiCr sheet of 0.025-0.051 cm. (0.010-0.020 in.) thickness except for the number of sheets per pack. Instead of the four sheets per pack which is optimum for 0.025-0.051 cm. (0.010-0.020 in.) sheet, eight sheets were employed utilizing this pack procedure.

Eight sheets of 0.0203 cm. (0.008 in.) foil and sixteen sheets of 0.0128 cm. (0.0055 in.) foil were produced utilizing the pack procedure and isothermal rolling in the 704°C to 760°C (1300°F to 1400°F) temperature range. Typical warm rolled 0.0128 cm. (0.0055 in.) foil is shown in Figure 56.

General surface appearance of these pieces of foil were comparable to that attained on typical 0.025 cm. (0.010 in.) "as-rolled" sheet. Only a few surface flaws were encountered from rolled-in TDNiCr and canning material.

Flatness appeared excellent on all sheets prior to any edge or end trimming.

Warm pack rolling in the 704-760°C (1300-1400°F) temperature range of unrecrystallized warm rolled 0.025 cm. (0.010 in.) sheet was carried out to a foil gauge of 0.0076 cm. (0.003 in.). General surface appearance of this material did not approach the quality obtained on the previously rolled

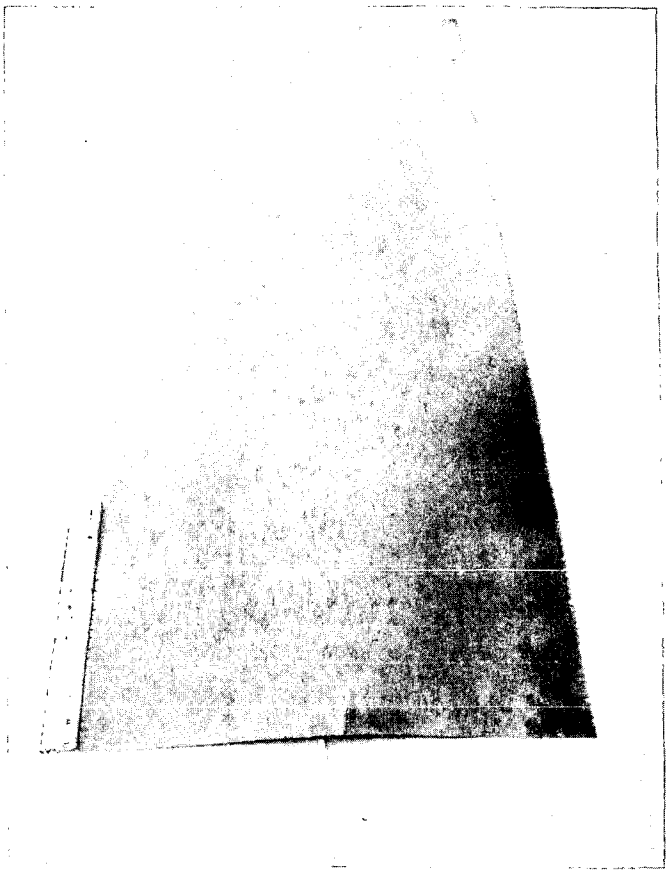


FIGURE 56

AS-WARM ROLLED 0.0128 cm.(0.0055 in.) TDNiCr FOIL

0.0203 and 0.0128 cm. (0.008 and 0.0055 in.) foil. Many rolled-in fragments of steel and/or TDNiCr were present accounting for a loss of about 30 percent of the foil after trimming out defects. This difficulty might be minimized by more frequent canning and recanning, or by use of aluminized steel in place of mild steel.

Gauge uniformity of 0.0203 cm. (0.008 in.) foil was found to be plus 8 percent, minus 14 percent from nominal. The 0.0128 cm. (0.0055 in.) foil had a gauge deviation of plus 7 percent, minus 10 percent from nominal. The greater minus deviations, from nominal thickness, indicate that in warm canned rolling the nominal gauge attained is heavier than had been anticipated.

Gauge uniformity and flatness of the 0.0076 cm. (0.003 in.) foil were found to be comparable to that attained on the 0.0128 and 0.0203 cm. (0.0055 and 0.008 in.) foil.

Metallographic examination of recrystallized 0.0203 and 0.0128 cm. (0.008 and 0.0055 in.) foil revealed a coarse grained structure being primarily one grain across the thickness of the sheet.

General mechanical property data were obtained on recrystallized warm rolled foil at 0.0203, 0.0128, and 0.0076 cm. (0.008, 0.0055 and 0.003 in.) foil. These data are shown in Table 61. The strength properties are lower than for thin sheet particularly at room temperature.

TABLE 61

MECHANICAL PROPERTIES OF WARM ROLLED TDNiCr FOIL

Heat No.	Gauge cm.	Room Temperature UTS MN/m^2	Room Temperature YS MN/m^2	Room Temperature Elong. % cm.	1093°C UTS MN/m^2	1093°C YS MN/m^2	1093°C Elong. % cm.	Min. Bend Radii	1093°C Stress Rupture @31.0MN/m^2 >20 Hrs.
3437	0.0203	744.1	512.6	17.0	80.6	80.6	2.5	2.0T	OK
3437	0.0140	643.5	512.6	8.0	88.9	88.9	2.5	1.2T	OK
3438	0.0076	689.0	388.6	10.0	121.3	121.3	2.6	<2.0T	OK

TABLE 61

MECHANICAL PROPERTIES OF WARM ROLLED TDNiCr FOIL

Heat No.	Gauge in.	Room Temperature UTS ksi	Room Temperature YS ksi	Room Temperature Elong. %-in.	2000°F UTS ksi	2000°F YS ksi	2000°F Elong. %-in.	Minimum Bend Radius	2000°F Stress Rupture @ 4500 psi >20 Hrs.
3437	0.0080	108.0	74.4	17.0	11.7	11.7	2.5	2.0T	OK
3437	0.0055	93.4	74.4	8.0	12.9	12.9	2.5	1.2T	OK
3438	0.0030	100.0	56.4	10.0	17.6	17.6	2.6	<2.0T	OK

(2.) Cold Tension Rolling

Cold tension rolling was performed on the single cluster configuration of the Schloemann Mill utilizing 15.24 cm. (6 in.) diameter work rolls having a 0.0025 cm. (0.001 in.) crown.

Four sheets of warm rolled and recrystallized 0.025 cm. (0.010 in.) sheet from Heat 3439 were processed by this technique into foil. Two of these sheets were rolled to 0.0203 x 38.10 x 101.60 cm. (0.008 x 15 x 40 in.) and the remaining two sheets were rolled to 0.0152 x 38.10 x 142.24 cm. (0.006 x 15 x 56 in.). The foil was then heat treated at 1177°C (2150°F). One piece of each gauge was hand polished by Scotch Brite technique prior to rolling in order to determine effect of conditioning the warm rolled-recrystallized finish prior to cold finishing. No difference in surface condition could be determined subsequent to cold rolling.

Figures 57 and 58 show the as-warm rolled 0.025 cm. (0.010 in.) starting material with and without the Scotch Brite polish.

Figures 59 and 60 show 0.0203 and 0.0152 cm. (0.008 and 0.006 in.) foil typical of that cold tension rolled on the Schloemann Mill.

No difference in surface appearance could be noted as a result of the Scotch Brite polish. However, a reduction of 20 percent was required to eliminate the previous warm rolled finish appearance of the starting warm-rolled 0.025 cm. (0.010 in.) sheet.

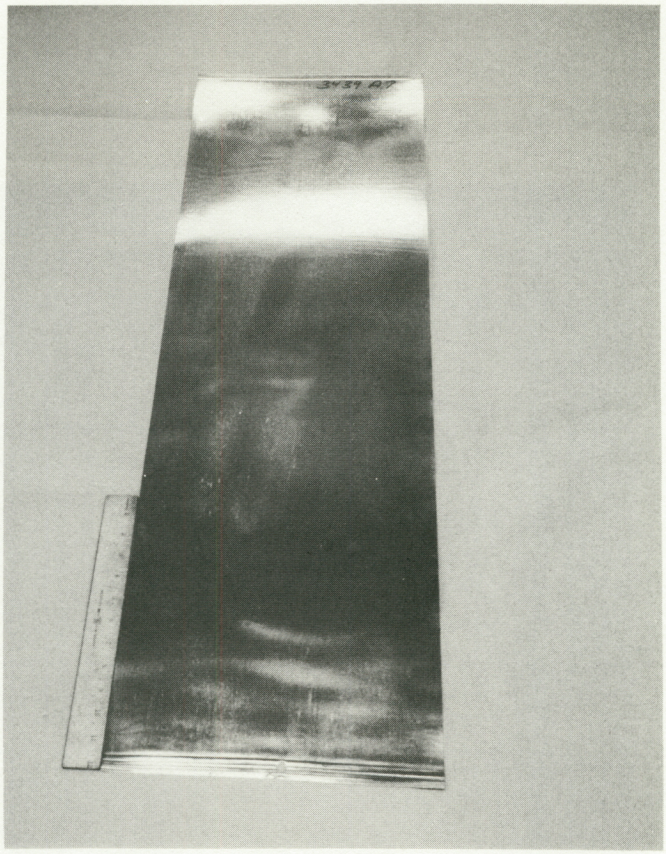


FIGURE 57

AS-WARM ROLLED AND SCOTCH BRITE POLISHED

0.025 cm.(0.010 in.) TDNiCr SHEET

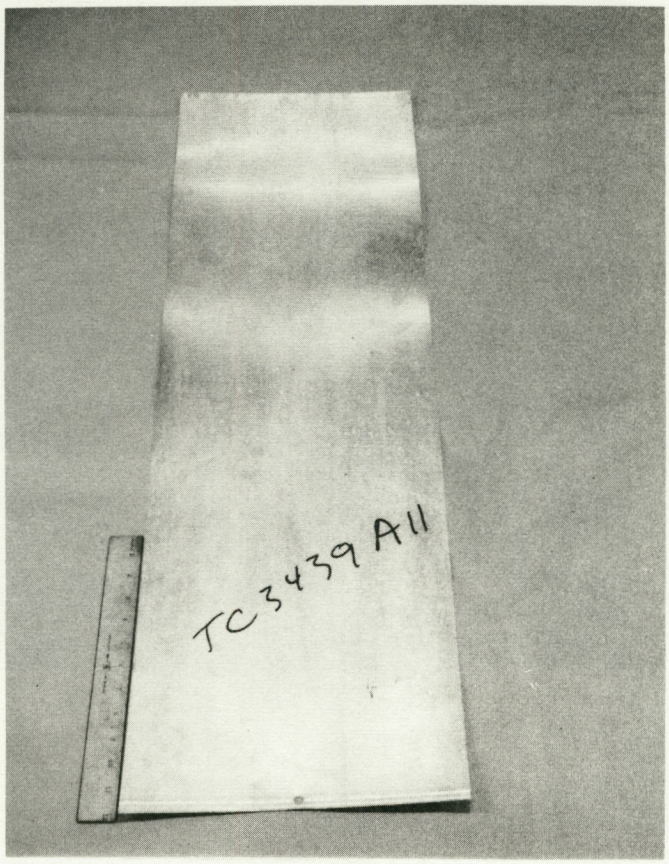


FIGURE 58

AS-WARM ROLLED

0.025 cm.(0.010 in.) TDNiCr SHEET



FIGURE 59

SCHLOEMANN COLD TENSION ROLLED
0.0203 cm.(0.008 in.) TDNiCr FOIL



FIGURE 60

SCHLOEMANN COLD TENSION ROLLED
0.0152 cm.(0.006 in.) TDNiCr FOIL

Mechanical properties of this material are presented in Table 62. It should be noted that as cold work is increased, strength at both room temperature and elevated temperature also increase. However, ductility as determined by bend testing decreases as cold work is increased.

As previously mentioned, it was noted that a minimum of about 20 percent cold reduction was necessary to eliminate the surface condition established during warm rolling. This is evident in the data presented in Table 63 which shows surface finish in terms of rms as a function of surface conditioning and cold reduction. As indicated on foil from Heat 3439 no significant improvement in surface finish was detected with cold reductions in excess of 20 percent. Further, the use of Scotch-Brite type polishing did not tend to improve surface finish as defined by rms indications, but general appearance was improved.

Further work carried out on the Baltimore Schloemann Mill by cold tension rolling included the cold reduction of one sheet of recrystallized warm-rolled 0.0128 cm. (0.0055 in.) foil to 0.0127 cm. (0.0050 in.) in thickness. Although the surface was improved the shape of the sheet was poorer. It was found that 0.0127 cm. (0.0050 in.) was the minimum gauge attainable.

In addition, two recrystallized warm rolled sheets of 0.0076 cm. (0.0030 in.) foil were pack, cold tension rolled on the Schloemann. This effort was unsuccessful due to sheet shape, tension control and pinching of the pack.

TABLE 62

MECHANICAL PROPERTIES OF COLD TENSION ROLLED TDNiCr FOIL

Heat No.	Gauge cm.	Condition	Room Temperature UTS MN/m^2	Room Temperature YS MN/m^2	Room Temperature Elong. % cm.	1093°C UTS MN/m^2	1093°C YS MN/m^2	1093°C Elong. % cm.	Min. Bend Radii	1093° Stress Rupture @31.0MN/m^2 >20 Hrs.
3439	0.025	Warm Rolled Rx	824.7	507.8	18.1	115.8	-	2.2	3.0T	OK
3439	0.0203	Cold Rolled 20%-H.T.	887.4	817.2	12.6	132.3	132.3	2.5	4.0T	OK
3439	0.0152	Cold Rolled 40%-H.T.	912.2	825.4	14.0	152.9	149.5	2.4	5.2T	OK

TABLE 62

MECHANICAL PROPERTIES OF COLD TENSION ROLLED TDNiCr FOIL

Heat No.	Gauge in.	Condition	Room Temperature UTS ksi	Room Temperature YS ksi	Room Temperature Elong. %- in.	2000°F UTS ksi	2000°F YS ksi	2000°F Elong. %- in.	Min. Bend Radii	2000°F Stress Rupture @4500 psi >20 Hrs.
3439	0.010	Warm Rolled Rx	119.7	73.7	18.1	16.8	-	2.2	3.0T	OK
3439	0.008	Cold Rolled 20%-H.T.	128.8	118.6	12.6	19.2	19.2	2.5	4.0T	OK
3439	0.006	Cold Rolled 40%-H.T.	132.4	119.8	14.0	22.2	21.7	2.4	5.2T	OK

TABLE 63

SURFACE FINISH AS A FUNCTION OF SURFACE CONDITIONING AND COLD REDUCTION

Heat No.	Gauge cm.	Gauge in.	Process Condition	Surface Finish rms Long.	Surface Finish rms Trans.
3437	0.0203	0.0080	Warm Rolled	60	43
3437	0.0203	0.0080	Warm Rolled & Scotch-Brite	70	38
3437	0.0140	0.0055	Warm Rolled	38	26
3437	0.0140	0.0055	Warm Rolled & Scotch-Brite	41	33
3437	0.0076	0.0030	Warm Rolled	55	26
3437	0.0076	0.0030	Warm Rolled & Scotch-Brite	40	31
3437	0.0140	0.0055	Cold Reduced to 0.0127 cm.(0.0050 in.)	9	14
3437	0.0140	0.0055	Cold Reduced to 0.0127 cm.(0.0050 in.) & Scotch-Brite	8	13
3437	0.0140	0.0055	Cold Reduced to 0.0127 cm.(0.0050 in.) & Scotch-Brite	8	13
3437	0.0203	0.0080	Cold Reduced to 0.0165 cm.(0.0065 in.)	-	12
3437	0.0203	0.0080	Cold Reduced to 0.0165 cm.(0.0065 in.) & Scotch Brite	12	13
3439	0.025	0.010	Cold Reduced to 0.0203 cm.(0.008 in.)	6	-
3439	0.025	0.010	Cold Reduced to 0.0203 cm.(0.008 in.) & Scotch-Brite	7	11
3439	0.025	0.010	Cold Reduced to 0.0152 cm.(0.006 in.)	7.5	9
3439	0.025	0.010	Cold Reduced to 0.0152 cm.(0.006 in.) & Scotch-Brite	6	8

b. North Chicago Foil Rolling

The objective of this portion of the program was to evaluate the feasibility of rolling 0.0051-0.0127 cm. (0.002-0.005 in.) foil having a 30.48 cm. (12 in.) width and minimum of 114.62 cm. (48 in.) length. This work was to be accomplished on a 30.48 cm. (12 in.) Sendzimir Mill.

Initially, ten 0.025 x 30.48 x 96.52 cm. (0.010 x 12 x 38 in.) recrystallized sheets of Heat 3439 were cold tension rolled and heat treated at 1177°C (2150°F). Certain problems were encountered in obtaining satisfactory shape in the sheets. Subsequent to one pass of approximately 10 percent reduction, a "herringbone-like" pattern developed in the center 25.40 cm. (10 in.) width of the sheet. An example of this pattern is shown in Figure 61, a sheet of 0.0076 cm. (0.003 in.) foil cold tension rolled on the Sendzimir Mill.

Some success in eliminating this difficulty was achieved with increased front and back tension. This approach, however, resulted in higher frequency of strip breakage. Only one strip of 0.0051 x 30.48 x 152.40 cm. (0.002 x 12 x 60 in.) foil was produced with no "herringbone-like" pattern. The majority of the remaining strips broke prior to attainment of the 0.0051 cm. (0.002 in.) thickness.

It was believed that roll shape of the intermediate work rolls was partially responsible for the "herringbone-like" pattern. Various combinations of roll shapes were utilized, but only minor improvement was noted. Future rolling will concentrate on evaluating effect of other combinations of roll shapes upon sheet shape.

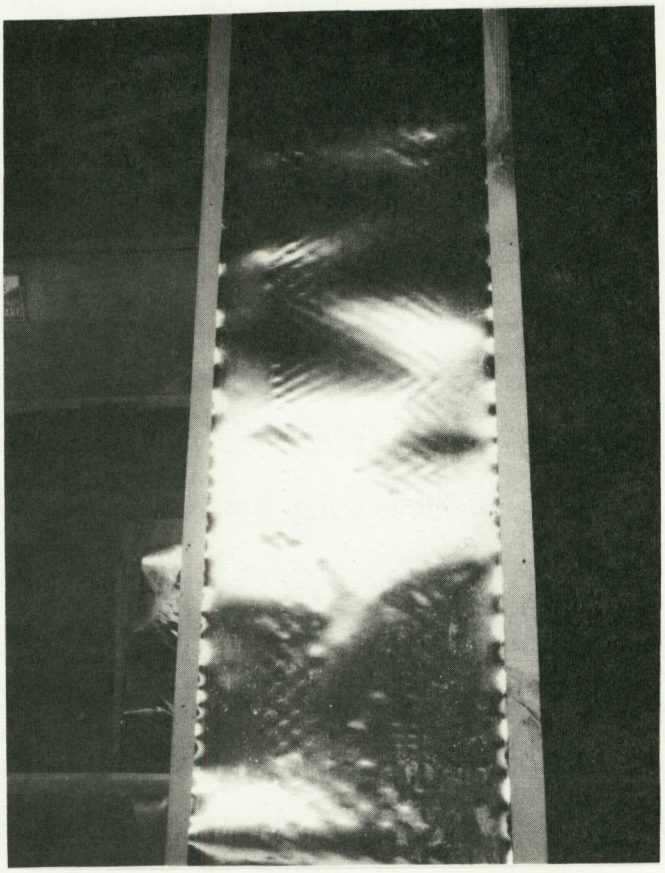


FIGURE 61

SENDZIMIR COLD TENSION ROLLED 0.0076 cm.(0.003 in.)
TDNiCr FOIL SHOWING "HERRINGBONE-LIKE" PATTERN

Mechanical properties of foil less than 0.0127 cm. (0.0050 in.) previously rolled at North Chicago on the Sendzimir Mill are presented in Table 64.

c. Toll Foil Rolling

Scale up of TDNiCr foil to widths greater than 30.48 cm. (12 in.) was initiated at Rodney Metals of New Bedford, Mass. A total of ten sheets were rolled to explore the scale-up potential of wide foil and to evaluate the effect of utilizing material which had a large ThO_2 size (>15 mμ) at the 2.54 cm. (1.0 in.) slab stage. Previous foil rolling had been performed only on fine ThO_2/large grain sheet.

The heats, gauges, and sizes of the sheets rolled are listed below. All were warm rolled-recrystallized.

Heat No.	Gauge cm.	Gauge in.	No. of pcs.	Width cm.	Width in.	Length cm.	Length in.
3528	0.025	0.010	8	52.07	20-1/2	114.30-121.92	45-48
3437	0.0128	0.0055	1	45.72	18	119.38	47
3523	0.025	0.010	1	60.96	24	182.90	72

A 60.96 cm. (24 in.) Reliance Sendzimir Mill was utilized for this rolling. The work rolls, which were 5.08 cm. (2 in.) in diameter, were a high carbon, high chrome die steel. Roll crowns on the work rolls were varied according to the width. They were 0.0127 cm. (0.005 in.) for 45.72 cm. (18 in.) wide sheet, 0.0076 cm. (0.003 in.) for 52.07 cm. (20-1/2 in.) wide sheet, and 0.0051 cm. (0.002 in.) for 60.96 cm. (24 in.) wide sheet. Intermediate rolls were approximately 10.16 cm. (4 in.) in diameter and had a 45.72 cm. (18 in.) central flat

TABLE 64

MECHANICAL PROPERTIES OF COLD TENSION SENDZIMIR ROLLED TDNiCr FOIL

Heat No.	Gauge cm.	Condition	Room Temperature UTS MN/m^2	Room Temperature YS MN/m^2	Room Temperature Elong. % cm.	1093°C UTS MN/m^2	1093°C YS MN/m^2	1093°C Elong. % cm.	Min. Bend	1093°C Stress Rupture @ 31.0MN/m^2 >20 Hrs.
3439	0.025	Warm Rolled Rx	824.7	507.8	18.1	115.8	-	2.2	3.0T	OK
3439	0.0102	Cold Rolled 60% H.T.	878.5	770.3	4.0	81.3	77.9	5.5	<1.5T	OK
3439	0.0061	Cold Rolled 76% H.T.	830.9	785.5	1.0	71.0	64.1	0.4	<1.5T	OK
3439	0.0051	Cold Rolled 80% H.T.	689.0	689.0	2.5	60.6	56.5	8.8	<1.5T	OK

TABLE 64

MECHANICAL PROPERTIES OF COLD TENSION SENDZIMIR ROLLED TDNiCr FOIL

Heat No.	Gauge in.	Condition	Room Temperature UTS ksi	Room Temperature YS ksi	Room Temperature Elong. %-in.	2000°F UTS ksi	2000°F YS ksi	2000°F Elong. %-in.	Min. Bend	2000°F Stress Rupture @ 4500 psi >20 Hrs.
3439	0.010	Warm Rolled Rx	119.7	73.7	18.1	16.8	-	2.2	3.0T	OK
3439	0.0040	Cold Rolled 60% H.T.	127.5	111.8	4.0	11.8	11.3	5.5	<1.5T	OK
3439	0.0024	Cold Rolled 76% H.T.	120.6	114.0	1.0	10.3	9.3	0.4	<1.5T	OK
3439	0.0020	Cold Rolled 80% H.T.	100.0	100.0	2.5	8.8	8.2	8.8	<1.5T	OK

with a 0.002 cm/cm(2 mil/inch) taper on each end. Strip speeds varied from 5.1 cm. (2 in.) per second to 25.4 cm. (10 in.) per second, with the higher speeds possible only on long strips. Seam welded stainless steel leader strip, approximately the same thickness as the initial TDNiCr thickness, was used to provide sufficient length for attachment to take-up spools. Ten to thirteen passes were required to reach a gauge of 0.0114 cm. (0.0045 in.) starting from 0.025 cm. (0.010 in.), an average reduction per pass of 8%. Screwdown pressures were from 0.051-0.34 MN/m^2 (75-500 psi), and generally were increased with decreasing gauge. Both front and back strip tensions were approximately equal and reached 30% of the yield point at the smaller gauges.

Processing was initiated on 52.07 cm. (20-1/2 in.) wide sheets. It was found that a 55% reduction to 0.0114 cm. (0.0045 in.) was the maximum reduction possible without encountering a high frequency of strip breakage. This number agrees with that of the North Chicago foil rolling.

At this gauge, a noticeable "herringbone" pattern did exist, but not to the degree of 30.48 cm. (12 in.) wide foil. The goal was to produce 0.0051-0.0076 cm. (0.002-0.003 in.) material and, therefore, 0.0114 cm. (0.0045 in.) foil was strand annealed in hydrogen at 1121°C(2050°F) for approximately one minute at Rodney. After the heat treatment edge slitting was done to remove small cracks approximately 0.158 cm. (1/16 in.) deep. Rolling was continued to 0.0061-0.0084 cm. (0.0024-0.0033 in.) and was followed by another heat treatment.

Figure 62 is a photograph of the longest sheet produced in this width. Its dimensions are 0.0076 x 52.70 x 325.12 cm. (0.003 x 20-3/4 x 128 in.). A slight herringbone pattern is evident, but comparison with a similar picture of 30.48 cm. (12 in.) wide foil in the previous section does show a marked improvement. The shape of this sheet is typical of all of the 52.07 cm. (20-1/2 in.) wide material.

Table 65 gives a summary of the average gauges and gauge uniformity for these sheets.

In addition to the above, one 0.0140 x 45.72 x 119.38 cm. (0.0055 x 18 x 47 in.) sheet and one 0.025 x 60.96 x 182.88 cm. (0.010 x 24 x 72 in.) sheet were rolled to foil. The first piece was rolled to 0.0076 cm. (0.003 in.) with a work roll crown of 0.0127 cm. (0.005 in.). The starting sheet did not have as good a shape as those previously mentioned. The rolling was done directly to gauge without an intermediate anneal, as had been used on previous wide sheet.

For the 60.96 cm. (24 in.) wide sheet of Heat 3523 a processing sequence similar to that used for 52.07 cm. (20-1/2 in.) sheet was planned. However, the problem of different width was again encountered and a poor shape at 0.0132 cm. (0.0052 in.) was the result. Rolling was discontinued at this gauge because of sheet breakage. Scale-up to 60.96 cm. (24 in.) will require small changes in work roll crown. The optimum crown will be established when several 60.96 cm. (24 in.) wide 0.025 cm. (0.010 in.) sheets become available.

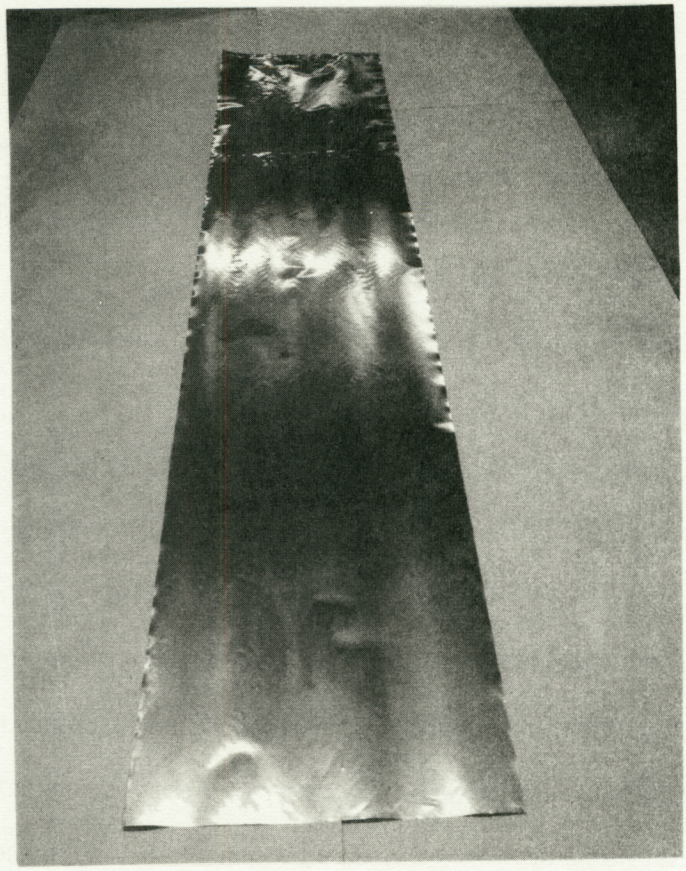


FIGURE 62

TDNiCr FOIL ROLLED AT RODNEY METALS

0.0076 x 52.70 x 320.04 cm.
(0.003 x 20-3/4 x 126 in.)

C-E

TABLE 65

SUMMARY OF TDNiCr FOIL SIZES

Sheet No.	Avg. Gauge cm.	Avg. Gauge in.	Width cm.	Width in.	Length cm.	Length in.	Max. Gauge cm.	Max. Gauge in.	Min. Gauge cm.	Min. Gauge in.	% Deviation
3528-1	0.0066	0.0026	53.34	21	102.87	40-1/2	0.0069	0.0027	0.0061	0.0024	+4, -8
3528-2	0.0069	0.0027	51.43	20-1/4	172.72	68	0.0071	0.0028	0.0066	0.0026	+4, -4
3528-3	0.0071	0.0028	52.07	20-1/2	182.88	72	0.0074	0.0029	0.0069	0.0027	+4, -4
3528-4	0.0079	0.0031	52.07	20-1/2	162.56	64	0.0084	0.0033	0.0076	0.0030	+6, -3
3528-5	0.0079	0.0031	52.70	20-3/4	149.86	59	0.0081	0.0032	0.0076	0.0030	+3, -3
3528-6	0.0081	0.0032	52.70	20-3/4	325.12	128	0.0086	0.0034	0.0076	0.0030	+6, -6
3528-7	0.0081	0.0032	52.07	20-1/2	261.62	103	0.0084	0.0033	0.0079	0.0031	+3, -3
3528-8	0.0066	0.0026	50.80	20	139.70	55	0.0069	0.0027	0.0064	0.0025	+4, -4
3528-9	0.0064	0.0025	52.07	20-1/2	200.60	79	0.0069	0.0027	0.0061	0.0024	+8, -4

Table 66 is a summary of the mechanical properties for the foil rolled. The properties are approximately equivalent to those achieved on small ThO_2 size foil which was produced by a different processing route. Although there are no goal strength properties for foil of less than 0.0127 cm. (0.005 in.) thick, the properties achieved are considered good. The 1093°C(2000°F) tensile strengths range from 59.9 to 95.1 MN/m^2 (8700 to 13,800 psi) and stress rupture life at 31.0 MN/m^2 (4500 psi) exceeds 20 hours. Bend ductility has been excellent on all foil less than 0.0127 cm. (0.0050 in.).

Figure 63 presents photomicrographs of Heats 3437 and 3528 at foil gauges ranging from 0.0066 to 0.0081 cm. (0.0026 to 0.0032 in.). Heat 3437, which had the highest elevated temperature strength, also had the largest grain size. Heat 3528 which exhibited somewhat lower properties, has a correspondingly smaller grain size.

Foil produced from Heat 3528 was used to fill a NASA requirement for 20 pcs. 30.48 x 60.96 x .0076 cm. (12 x 24 x 0.003 in.). Because the sheets were 52.07 cm. (20-1/2 in.) wide, they were sheared to length and maximum good width. Only one sheet required shearing to a 30.48 cm. (12 in.) width to eliminate a damaged edge.

To fulfill other requests for 0.0076 cm. (0.003 in.) material, the following pieces of TDNiCr sheet were sent to Rodney Metals and will be processed during Part II of this contract.

Heat No.	Gauge cm.	Gauge in.	No. of pcs.	Width cm.	Width in.	Length cm.	Length in.
3521	0.025	0.010	9	57.15	22-1/2	167.64-179.08	66-70-1/2
3522	0.025	0.010	7	49.13	19-1/2	155.57-164.36	61-1/4-64-3/4
3523	0.025	0.010	3	49.53	19-1/2	139.06-157.48	54-3/4-62
3524	0.025	0.010	4	49.53	19-1/2	139.06-139.70	54-3/4-55

All of the above were warm rolled and recrystallized at 0.025 cm.(0.010 in.).

d. TDNiCr Foil Summary

(1.) High strength TDNiCr foil can be produced in gauges from 0.0127 to 0.0229 cm. (0.005 to 0.009 in.) by warm pack rolling of unrecrystallized 0.025 cm.(0.010 in.) sheet.

(2.) Improvements in surface finish and appearance are possible on the above by cold tension rolling less than 20%. However, a minimum of 20% is required to completely remove all effects of warm rolling.

(3.) High quality foil in gauges from 0.0051 to 0.0127 cm. (0.002 to 0.005 in.) can be fabricated by cold tension rolling on a Sendzimir Mill in increments of 50-60% between anneals. Elevated temperature strengths are less than warm rolled material, but bend ductility is excellent.

e. TDNiCr Foil Recommendations

Improvements in foil production will be sought in Part II of this contract. They are:

TABLE 66

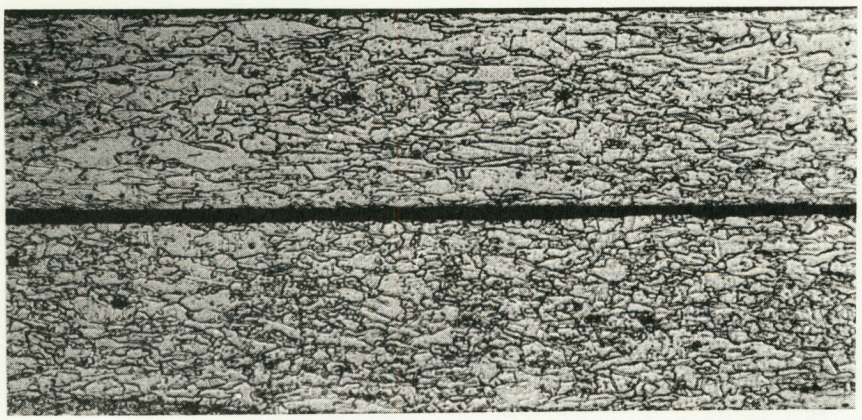
MECHANICAL PROPERTIES OF TDNiCr FOIL

Heat No.	Gauge cm.	Room Temperature Ftu MN/m^2	Fty MN/m^2	Elong. % cm.	1093°C Ftu MN/m^2	Fty MN/m^2	Elong. %	Min. Bend Radius	Stress Rupture at 31.0 Mn/m^2
3528-1	0.0066	804.1	755.8	2.0	68.9	64.1	4.0	<2T	OK
3528-4	0.0079	777.9	713.1	3.0	59.9	59.9	5.0	<2T	OK
3528-6	0.0081	918.4	868.8	2.5	66.8	66.8	3.5	<2T	OK
3528-9	0.0064	838.5	788.9	2.5	78.5	78.5	3.5	<2T	OK
3437-1	0.0071	858.5	858.5	1.5	95.0	95.0	3.0	<2T	OK
3523-1	0.0132	812.3	684.2	5.0	58.6	-	-	<2T	OK

TABLE 66

MECHANICAL PROPERTIES OF TDNiCr FOIL

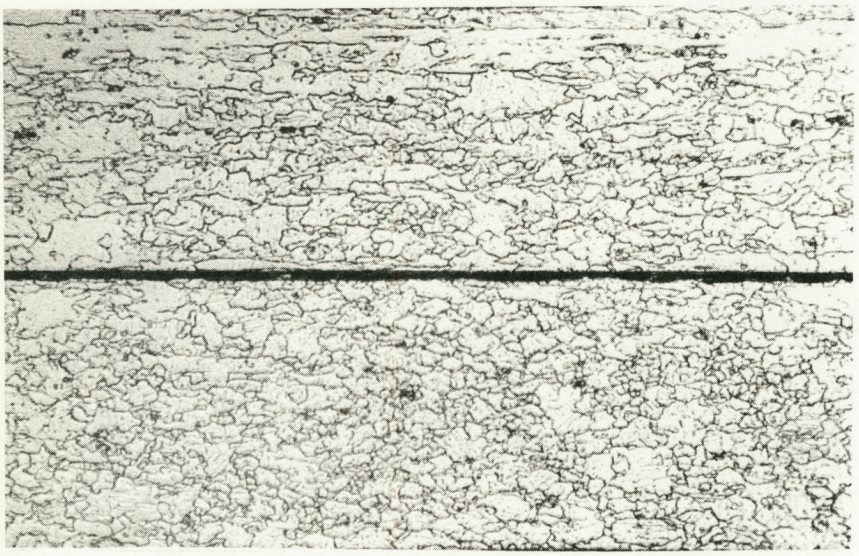
Heat No.	Gauge in.	Room Temperature Ftu ksi	Room Temperature Fty ksi	Room Temperature Elong. %	2000°C Ftu ksi	2000°C Fty ksi	2000°C Elong. %	Min. Bend Radius	Stress Rupture at 4500 psi
3528-1	0.0026	116.7	109.7	2.0	10.0	9.3	4.0	<2T	OK
3528-4	0.0031	112.9	103.5	3.0	8.7	8.7	5.0	<2T	OK
3528-6	0.0032	133.3	126.1	2.5	9.7	9.7	3.5	<2T	OK
3528-9	0.0025	121.7	114.5	2.5	11.4	11.4	3.5	<2T	OK
3437-1	0.0028	124.6	124.6	1.5	13.8	13.8	3.0	<2T	OK
3523-1	0.0052	117.9	99.3	5.0	8.5	-	-	<2T	OK



LONGITUDINAL

TRANSVERSE

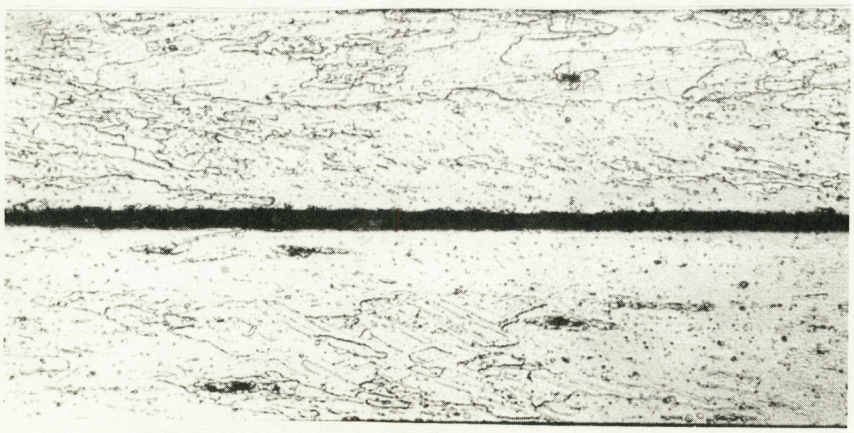
400X



LONGITUDINAL

TRANSVERSE

400X



LONGITUDINAL

TRANSVERSE

400X

HEAT 3437-1 0.0071 cm.(0.0028 in.)

FIGURE 63

MICROSTRUCTURES OF TDNiCr FOIL

(1.) Determination of the limit of cold work 0.025 cm. (0.010 in.) material can withstand without exceeding a 3T bend radius.

(2.) Scale up of 0.0127-0.0229 cm. (0.005-0.009 in.) foil to a 60.96 (24 in.) width and 0.0051-0.0127 cm. (0.002-0.005 in.) foil to widths greater than 30.48 cm. (12 in.).

(3.) Fabrication of 0.0051 to 0.0127 cm. (0.002 to 0.005 in.) foil with improved shape.

4. Rolling and Finishing Procedures

Work carried out in this area of study was run in conjunction with the TDNiCr Sheet Production Programs and the TDNiCr foil studies.

This work included such items as room temperature roll leveling, stretch leveling, cold roll finishing, in-process conditioning, and abrasive polishing. All of these procedures are discussed in other sections of this report.

However, two additional procedures evaluated and not discussed elsewhere in this report are Chemical Milling and Creep Flattening.

a. Chemical Milling

This work consisted of an evaluation of the effects of chemical milling TDNiCr sheet. Two full size, e.g. 45.72 x 91.44 cm. (18 x 36 in.) sheets of TDNiCr; Heat 3418 at 0.102 cm. (0.040 in.) and Heat 3387 at 0.025 cm. (0.010 in.), were chemically milled at Chemical Micro Milling Co. in Pennsauken, N.J. in January 1971.

Removal of material was accomplished by passing each sheet through three acid spray chambers on a conveyor type device. A final chamber was a water rinse chamber, the unit was too short to accommodate the 91.44 cm. (36 in.) length sheets thus requiring a hose rinse after exit from the unit. The etchant used was described as a modified Ferric Chloride of a proprietary nature. The time necessary to remove 0.0025 cm. (0.001 in.) per side was about three minutes with a solution temperature of 54°C (130°F).

It was reported that gauge uniformity would be no better than the as-received sheets and that edges and ends of sheets would tend to be more heavily etched from run off of the etchant. The results shown below verify these statements. In addition, surface finish tended to deteriorate, especially on the heavily etched sheet of Heat 3418 as indicated by profilometer measurements before and after chemical milling as shown below:

Heat No.	Initial Median Gauge cm.	Initial Median Gauge in.	Final Median Gauge cm.	Final Median Gauge in.	rms finish before milling Long.	rms finish before milling Trans.	rms finish after milling Long.	rms finish after milling Trans.
3418	0.104 ±.005	0.041 ±.002	0.084 ±.0076	0.033 ±.003	7-11	13-16	50-85	80-100
3487	0.025 ±.0025	0.010 ±.001	0.0203 ±.0025	0.008 ±.001	12-17	25-35	20-28	20-25

The general appearance of the chemical milled sheets exhibited a macro etch of the structure. This type of appearance was found to be aesthetically objectionable. It is shown in Figure 64.

In conclusion, no advantage for this type of finishing of TDNiCr sheet was evident.

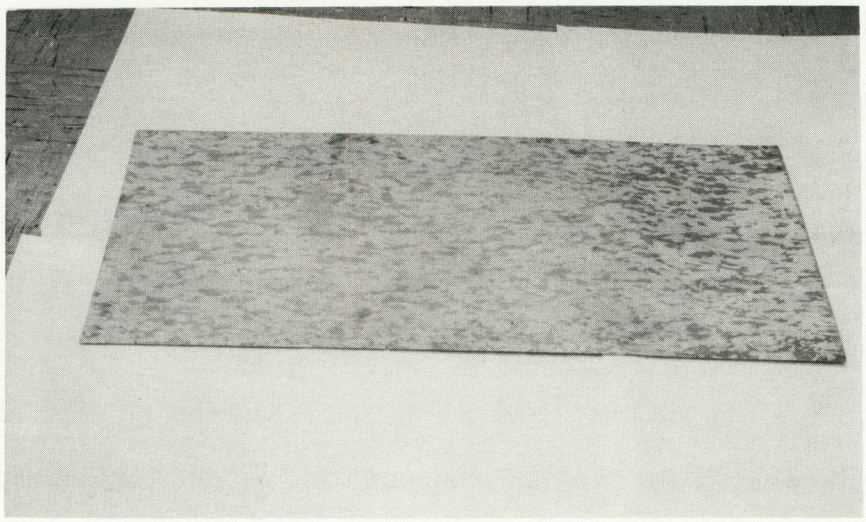


FIGURE 64

TDNiCr SHEET AT 0.084 cm.(0.033 in.) THICKNESS
AFTER CHEMICAL MILLING

HEAT 3418

b. Creep Flattening

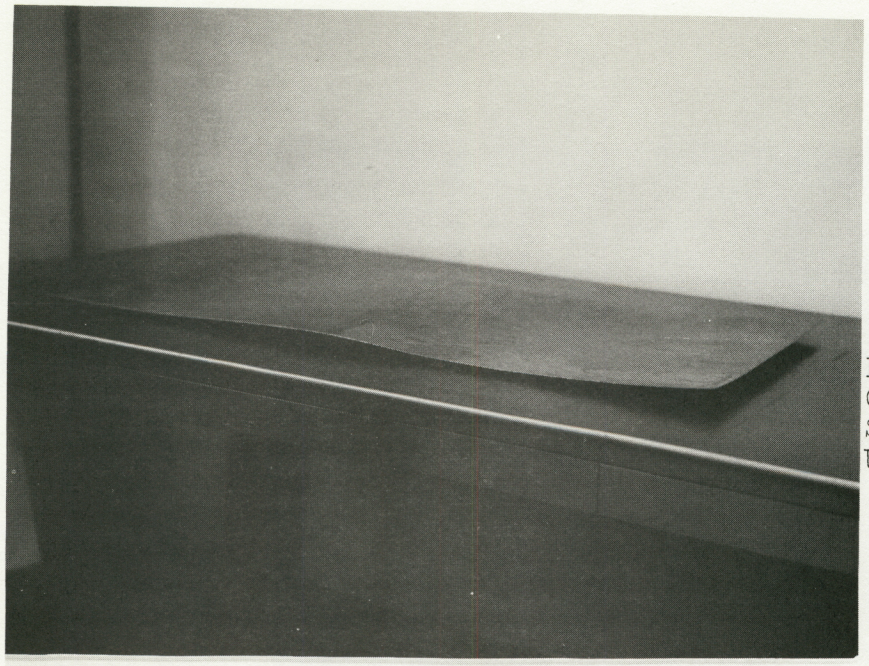
The use of "creep flattening" as a means of producing flat TDNiCr sheet was investigated. Several sheets were sent to the Titanium Metals Corp. of America in Toronto, Ohio during February, 1971. TMCA utilizes a vacuum creep flattening fixture for producing flat, stress-free titanium plate. The fixture was designed and built under contract by Boeing Co. Flattening is achieved by placing sheet on a flat refractory bed, covering it with insulating material, and vacuum sealing it at a temperature of 760°C(1400°F). Atmospheric pressure causes the plate to "creep" into a flattened condition and remain flat after removal from the fixture.

Four 45.72 x 91.44 cm. (18 x 36 in.) sheets of TDNiCr were sent to TMCA for creep flattening evaluation. The heat number, gauge and condition of each of the sheets was as follows:

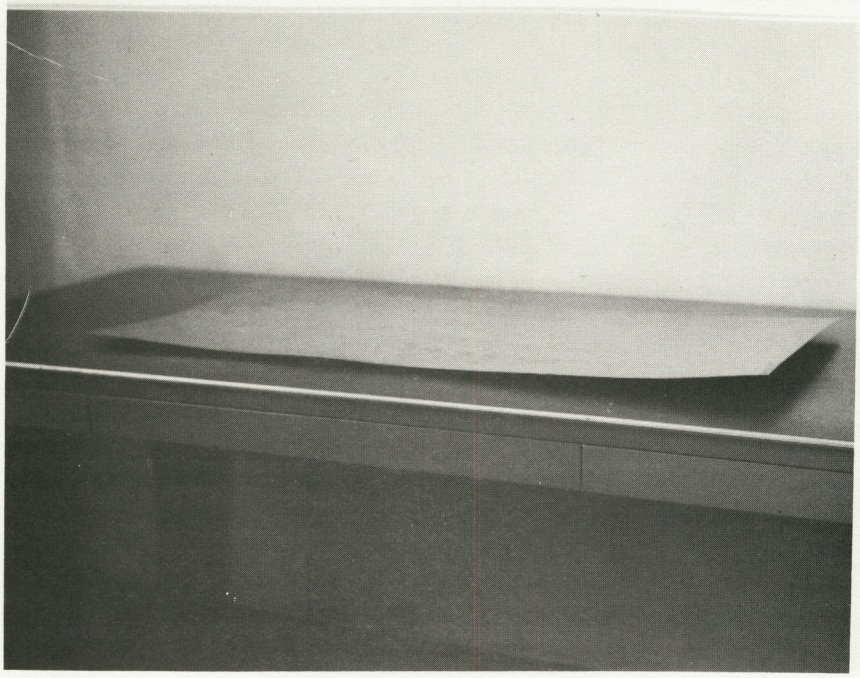
Heat 3444-A	0.102 cm.(0.040 in.)	as-warm rolled - unrecrystallized
Heat 3438-B	0.102 cm.(0.040 in.)	as-warm rolled - recrystallized
Heat 3454-A	0.046 cm.(0.018 in.)	as-warm rolled - unrecrystallized
Heat 3454-B	0.046 cm.(0.018 in.)	as-warm rolled - recrystallized

Figures 65 and 66 show general appearance of the 0.102 and 0.046 cm. (0.040 and 0.018 in.) sheets respectively as submitted to TMCA for creep flattening.

Upon return of the sheets subsequent to the creep flattening operation, it was readily noted that excellent flatness was obtained on both the 0.102 and 0.046 cm. (0.040 and 0.018 in.) sheets



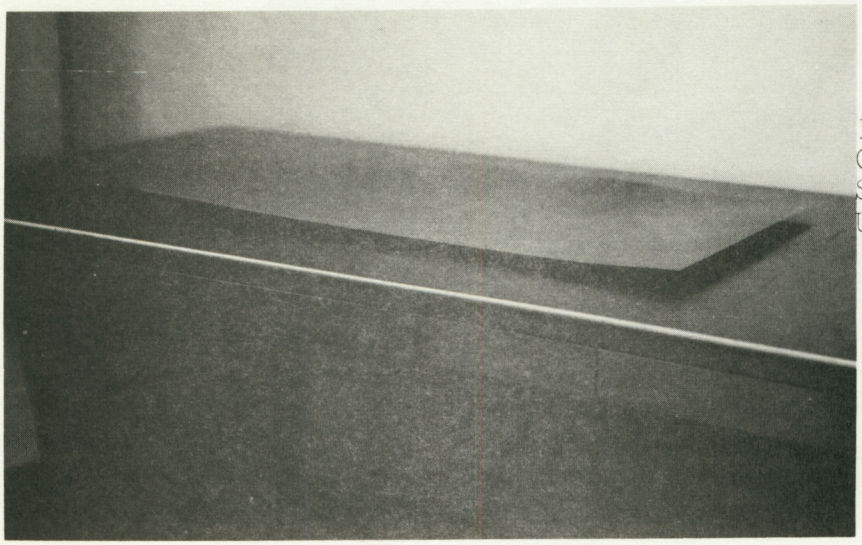
HEAT 3444-A
0.102 cm.(0.040 in.)
Sheet
Unrecrystallized



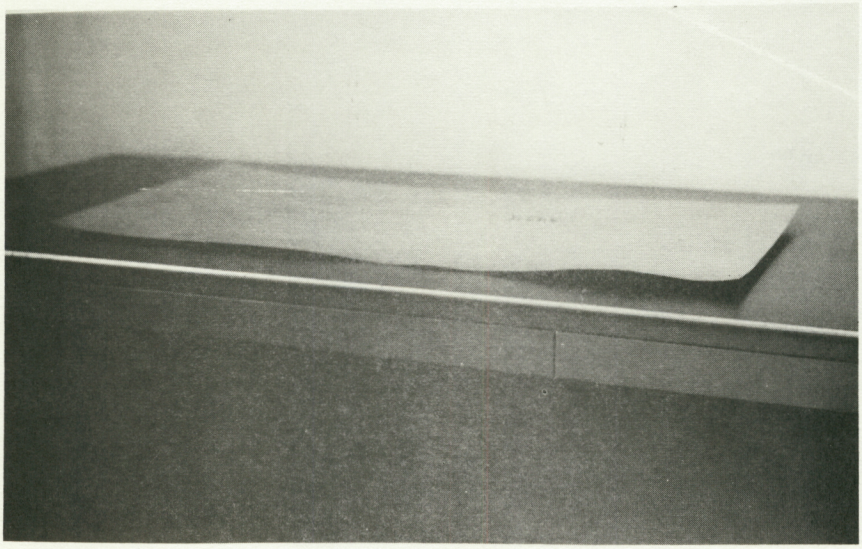
HEAT 3438-B
0.102 cm.(0.040 in.)
Sheet
Recrystallized

FIGURE 65

TDNiCr SHEET PRIOR TO CREEP FLATTENING



Heat 3454-A
0.046 cm.(0.018 in.)
Sheet
Unrecrystallized



Heat 3454-B
0.046 cm.(0.018 in.)
Sheet
Recrystallized

FIGURE 66

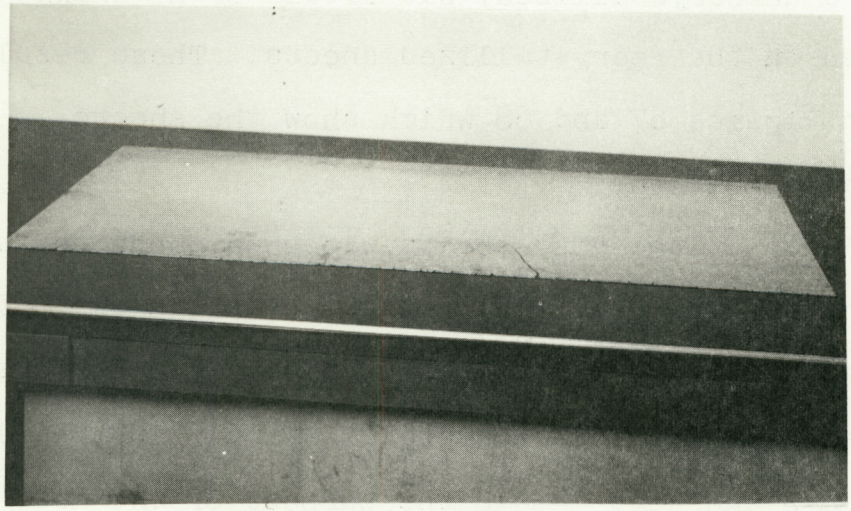
TDNiCr SHEET PRIOR TO CREEP FLATTENING

that were unrecrystallized, but little or no change in flatness was noted on the recrystallized sheets. These results may be noted in Figures 67 and 68 which show the sheets in the as-creep flattened condition.

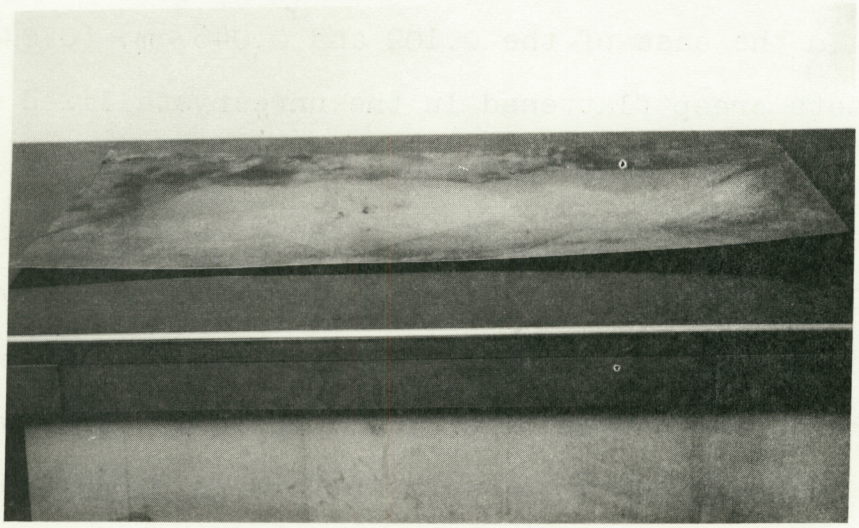
Each of the four sheets was then subjected to a heat treatment of 1177°C(2150°F) for two hours in dry hydrogen. In the case of Heat 3444-A and Heat 3454-A, the purpose of the heat treatment was for recrystallization. In the case of Heat 3438-B and Heat 3454-B the purpose of the heat treatment was for stress relief only.

In the case of the 0.102 and 0.046 cm. (0.040 and 0.018 in.) sheets creep flattened in the unrecrystallized condition, much of the improvement was lost as a result of the recrystallization heat treatment. In the case of the remaining two sheets little change in flatness, either better or worse was noted as a result of the final stress relief. These results may be noted in Figures 69 and 70. The edge crack which appears in Heat 3444-A in Figure 67 and in Figure 69 was attributed to improper handling during preparation of the flattening assembly.

This technique offers little potential for improving flatness. The technique might work quite well if the flattening could be combined with the 1177°C(2150°F) heat treatment for recrystallization; thus creep flattening and recrystallization taking place while the sheet remains in a perfectly flat configuration.



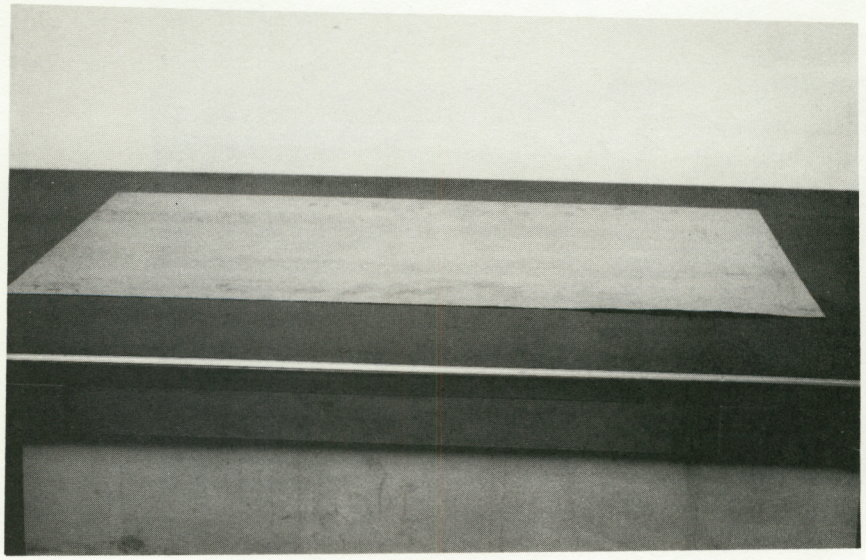
Heat 3444-A
0.102 cm.
(0.040 in.)
Sheet



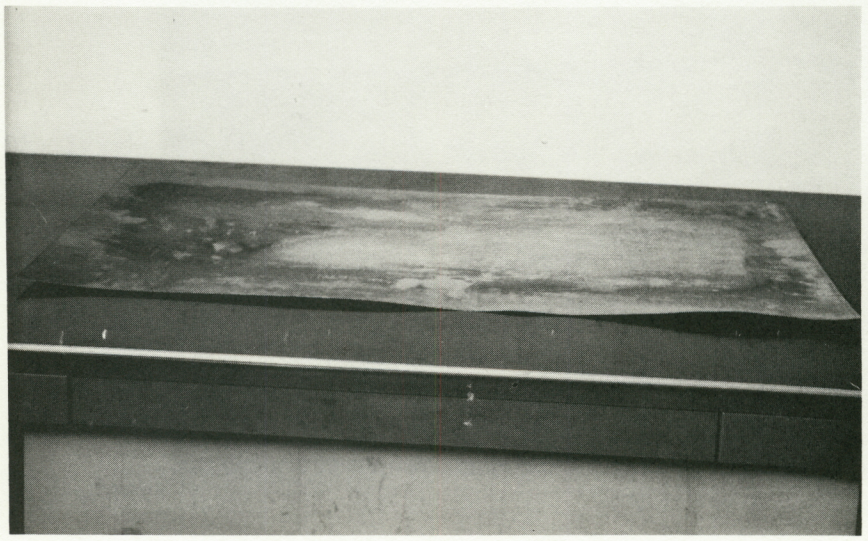
Heat 3438-B
0.102 cm.
(0.040 in.)
Sheet

FIGURE 67

TDNiCr SHEET AS-CREEP FLATTENED



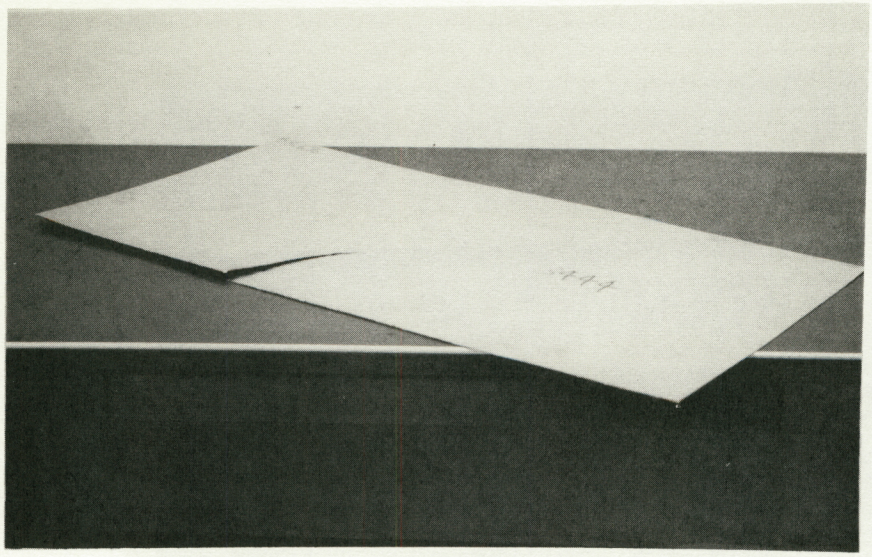
Heat 3454-A
0.046 cm.
(0.018 in.)
Sheet



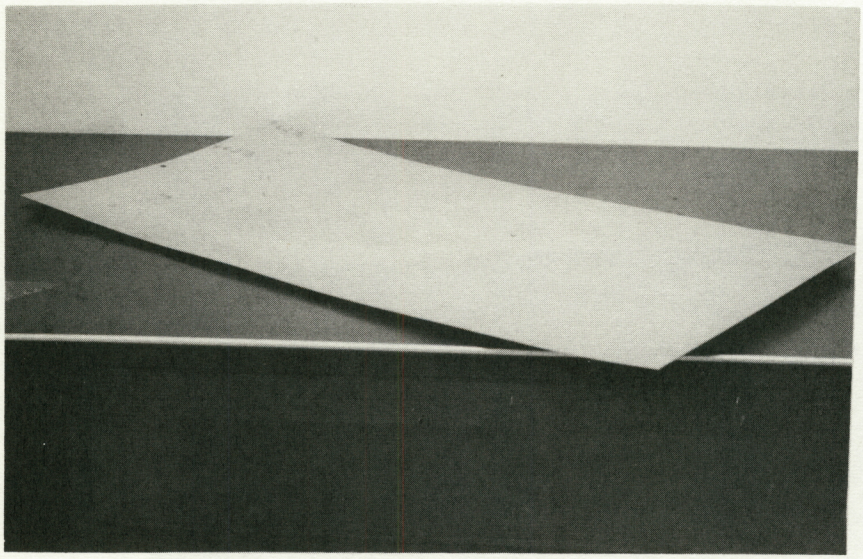
Heat 3454-B
0.046 cm.
(0.018 in.)
Sheet

FIGURE 68

TDNiCr SHEET AS-CREEP FLATTENED



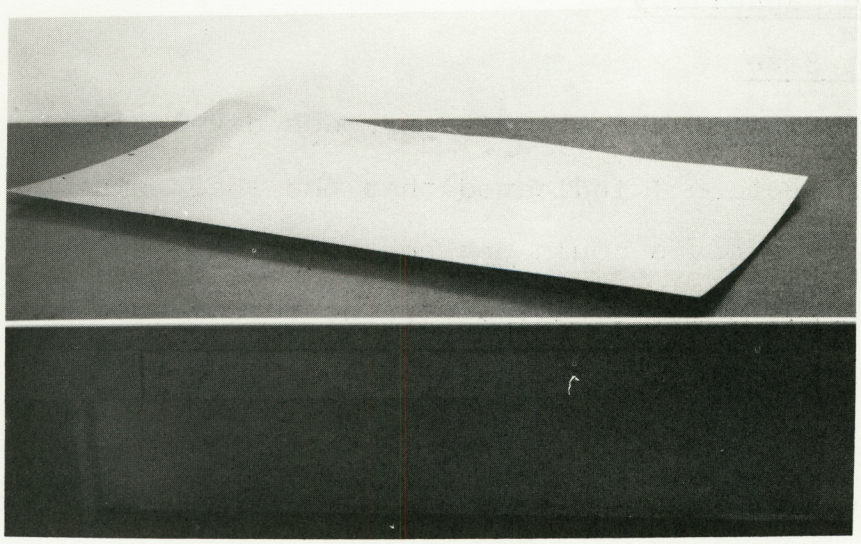
Heat 3444-A
0.102 cm.
(0.040 in.)
Sheet



Heat 3438-B
0.102 cm.
(0.040 in.)
Sheet

FIGURE 69

TDNiCr SHEET CREEP FLATTENED
AND SUBSEQUENTLY HEAT TREATED
AT 1177°C(2150°F) FOR 2 HRS.



Heat 3454-A
0.046 cm.
(0.018 in.)
Sheet

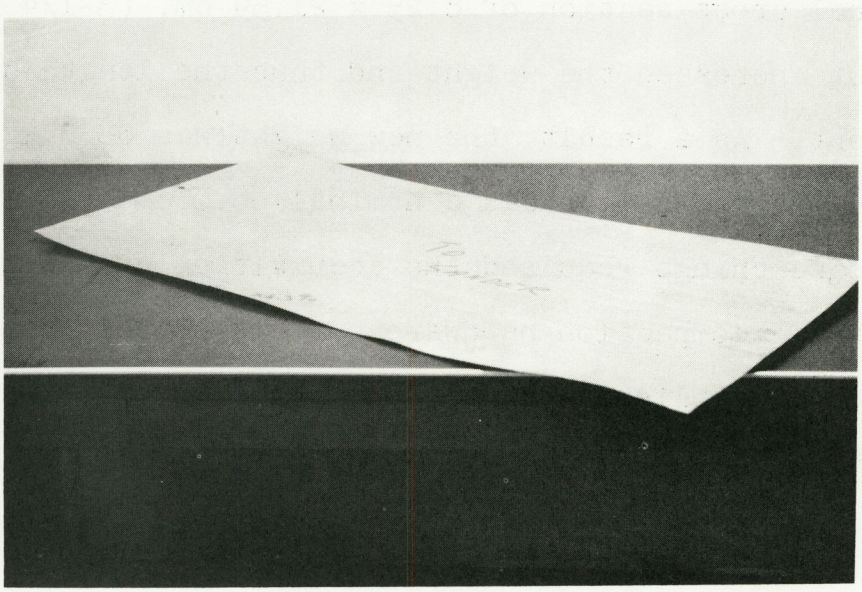


FIGURE 70

TDNiCr SHEET CREEP FLATTENED
AND SUBSEQUENTLY HEAT TREATED
AT 1177°C(2150°F) FOR 2 HRS.

5. Sheet Size Capability

a. Billet Size

The results of the standard process development carried out in Section I indicated that the sheet size capability program goals could not be achieved with the 45.4 kg. (100 lb.) units employed for the recommended finalized process. In order to make 60.96 x 152.40 cm. (24 x 60 in.) sheets over the gauge range from 0.025 to 0.102 cm. (0.010 to 0.040 in.) it was necessary to increase the starting billet size. The new size selected maintained the same nominal cross section of 8.25 x 21.59 cm. (3-1/4 x 8-1/2 in.), but increased the weight and thus the length by about 50 percent. As a result, the new weight was 68.0 kg. (150 lbs.) and the new length was a nominal 66.0 cm. (26 in.).

This size change required the acquisition of new larger hydrostatic compaction hardware but did not alter the standard process established for the 45.4 kg. (100 lb.) units in any other manner.

Three typical 68.0 kg. (150 lb.) units are shown in Figure 71.

b. Facilities

In addition to the necessity for an increased billet size to produce 60.96 x 152.4 cm. (24 x 60 in.) sheets, certain facilities were also required for the scale up. These facilities included furnacing and chemical cleaning lines.

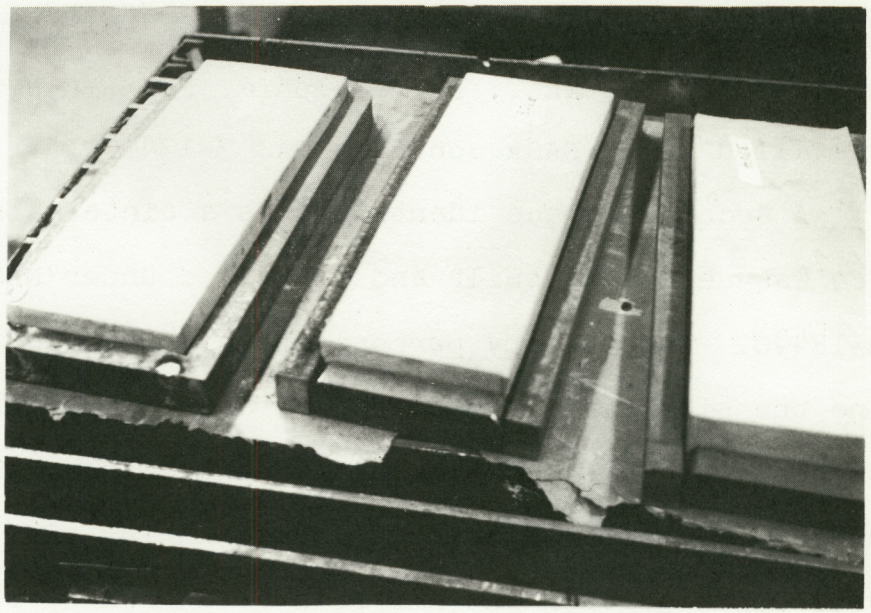


FIGURE 71

TYPICAL 68.0 kg.(150.0 lb.) HYDROSTATICALLY COMPACTED TDNiCr UNITS

Initial furnacing considered a warm rolling oven that would enable isothermal rolling of scaled up TDNiCr sheet in the temperature range of 538°C(1000°F) to 871°C (1600°F). The furnace selected to satisfy this requirement was built by Trent, Inc., Philadelphia, Pa. It was purchased and installed under NASA contract NAS 3-13490.

A second furnace identified as a sinter-consolidation furnace was designed, built and installed under NASA contract NAS 3-13490. The primary purpose of this furnace is to combine the sintering, consolidation and hot rolling breakdown operations into one step and thus eliminate the necessity of cooling down after sintering and recanning plus reheating for roll consolidation and hot roll breakdown of dispersion modified materials.

Fansteel also designed, built and installed an updated in-process and final product chemical conditioning area for specific use on dispersion modified materials.

Descriptions of the new facilities and their operation are given in APPENDIX E, New Facilities.

c. Scale-up Processing

Thirty 68.0 kg. (150 lb.) units of TDNiCr were compacted for this portion of the contract. Standard compaction techniques as employed for the 45.4 kg. (100 lb.) units and described in the finalized process section of this report were employed with the exception of new hardware to attain greater compact length and weight.

The initial ten units prepared included Heats 3519 through 3528. All of these heats except 3528 were fabricated according to the finalized process established in Section I and detailed in Sections I-2 and I-3 of this report. Heat 3528 was both sintered and roll consolidated at 1177°C(2150°F).

The primary purpose achieved during the fabrication of these ten units was familiarization of operating personnel with the larger units, the new Trent warm rolling oven and new chemical conditioning line. Further, all of the heats were processed to a final gauge of 0.025 cm. (0.010 in.) in order to establish yield data at various processing stages. Subsequent to compaction, each of the ten heats was loose can sintered, decanned and recanned in a conventional roll consolidation can as shown in Figure 14.

The units were preheated to 1010°C(1850°F) in H_2 at a dew point of -57°C(-70°F) or better. They were then roll consolidated by rolling in a direction parallel to the 21.59 cm. (8-1/2 in.) dimension, turned 90° and hot rolled to increase the nominal 67.31 cm. (26-1/2 in.) dimension to 76.20 cm. (30 in.), turned 90° and finish hot rolled to a nominal thickness of 2.54 cm. (1.0 in.).

At this stage of processing, the units were decanned, edge and end cropped and surface conditioned as required. Sizes and yields at the 2.54 cm. (1.0 in.) slab stage of processing are shown in Table 67. The slab thicknesses subsequent to surface conditioning do not reflect true surface condition as a function of clean up required because slab

TABLE 67

YIELD DATA FOR 68.0 kg.(150 lb.) TDNiCr UNITS

	2.54 cm.(1 in.) Slab Stage							Finish Gauge Sheet Width					
	cm.			in.				0.076-0.102 cm. (0.030-0.040 in.)		0.051-0.076 cm. (0.020-0.030 in.		0.025-0.051 cm. (0.010-0.020 in.)	
Heat	T	W	L	T	W	L	% Yield	cm.	in.	cm.	in.	cm.	in.
3519	2.03	69.69	35.88	0.800	27-7/16	14-1/8	70.3	54.61	21-1/2	52.39	20-5/8	49.53	19-1/2
3520	1.85	66.99	31.11	0.730	26-3/8	12-1/4	55.0					55.24	21-3/4
3521	2.48	71.44	30.48	0.975	28-1/8	12	66.5					57.15	22-1/2
3522	2.23	68.26	32.86	0.875	26-7/8	12-15/16	64.5	56.67	25-5/16	58.10	22-7/8	49.53	19-1/2
3523	2.23	72.39	33.34	0.875	28-1/2	13-1/8	67.2	67.63	26-5/8	66.99	26-3/8	62.23	24-1/2
3524	2.54	66.99	31.91	1.000	26-3/8	12-9/16	61.0	58.42	23			49.53	19-1/2
3525	1.91	62.23	35.56	0.750	24-1/2	14	55.0					46.35	18-1/4
3526	2.31	67.15	33.65	0.910	26-7/16	13-1/4	64.5	57.15	22-1/2	55.24	21-3/4	46.99	18-1/2
3527	1.87	63.50	34.29	0.735	25	13-1/2	53.6	50.32	19-13/16	47.62	18-3/4		
3528	2.54	67.15	30.48	1.000	26-7/16	12	63.1	60.96	24	54.61	21-1/2	52.07	20-1/2

flatness was a more critical factor contributing to final conditioned thickness.

Evaluation of yields at the 2.54 cm. (1.0 in.) slab stage of processing indicate that an average yield of 62.1 percent was attained. In comparison an average yield of 77.1 percent was attained at a similar stage of processing on sixteen 45.36 kg. (100 lb.) units fabricated by the same basic process. Detailed data on these heats are shown in Table 68.

Comparing the data presented in Tables 67 and 68, it may be noted that the higher yield experienced on the 45.36 kg. (100 lb.) units was attributed to less loss during surface conditioning as evidence by greater thicknesses on the smaller units. In addition, less edge and/or end losses were encountered on smaller units as evidenced by conditioned unit lengths and widths. A finished width of 55.88 to 58.42 cm. (22 to 23 in.) was sought and accomplished on the smaller units, while a 73.66 to 76.20 cm. (29 to 30 in.) finished width was desired but not attained on the larger units.

Further, lower yields on the larger units were felt to be somewhat dependent on this work being accomplished during early stages of the learning curve, while fabrication of the smaller units shown in Table 68 was accomplished with a great deal of background experience.

Again referring to Table 67, it may be noted that a finish gauge sheet width goal of 60.96 cm. (24 in.) was attained on only one heat of the ten processed. This heat

TABLE 68

YIELD DATA FOR 45.36 kg.(100 lb.) TDNiCr UNITS

Heat No.	2.54 cm.(1 in.) Slab Stage cm. T	W	L	in. T	W	L	% Yield
3626	2.63	55.56	29.53	1.035	21-7/8	11-5/8	80.2
3627	2.31	55.09	19.05	0.908	21-11/16	7-1/2	44.2
3628	2.67	54.93	28.57	1.050	21-5/8	11-1/4	79.1
3629	2.54	57.78	28.26	1.000	22-3/4	11-1/8	76.4
3630	2.61	64.77	26.67	1.025	25-1/2	10-1/2	84.2
3631	2.67	63.50	27.30	1.050	25	10-3/4	86.7
3632	2.67	59.69	27.30	1.050	23-1/2	10-3/4	81.0
3633	2.67	55.88	26.99	1.050	22	10-5/8	73.8
3634	2.54	60.64	25.24	1.000	23.7/8	9-15/16	68.6
3635	2.70	61.75	27.78	1.063	24-5/16	10-15/16	85.9
3636	2.63	64.77	26.67	1.035	25-1/2	10-1/2	85.9
3637	2.67	58.42	26.67	1.050	23	10-1/2	76.5
3638	2.69	59.69	27.30	1.060	23-1/2	10-3/4	80.1
3639	2.54	59.69	27.94	1.000	23-1/2	11	81.8
3640	2.54	58.74	27.30	1.000	23-1/8	10-3/4	80.2
3641	2.53	55.88	27.46	0.995	22	10-13/16	69.0

indicated that edge losses encountered during processing from 2.54 cm. (1.0 in.) slab stage of processing to a finish gauge sheet of 0.025 cm. (0.010 in.) amounted to 10.16 cm. (4 in.). The balance of the heats indicated edge losses during the same processing sequence as great as 18.73 cm. (7-3/8 in.), but for the most part approximately 15.24 cm. (6 in.) indicating a necessity of having a 2.54 cm. (1.0 in.) slab width of at least 76.20 cm. (30 in.) in order to fabricate 60.96 cm. (24 in.) wide 0.025 cm. (0.010 in.) thick sheet.

Goal sheet lengths of 152.40 cm. (60 in.) were readily attainable and presented no fabrication difficulties.

Mechanical property data for the 68.0 kg. (150 lb.) units discussed above are shown in Table 69. The data meet the specification requirements.

In an attempt to improve 2.54 cm. (1.0 in.) slab yields by minimizing edge and/or end cracking during the roll consolidation stage of processing, an additional seven 68.0 kg. (150 lb.) units were compacted, sintered and canned for roll consolidation by conventional techniques. However, the roll consolidation procedure was altered. Rather than rolling the units in a direction parallel to the 21.59 cm. (8-1/2 in.) dimension, the units were rolled in a direction parallel to the 67.31 cm. (26-1/2 in.) dimension. During this procedure, it was noted that excessive elongation of the unit took place on the consolidation pass, thus, causing extreme edge cracking and break out of the TDNiCr on the trailing end of the consolidation can.

TABLE 69

MECHANICAL PROPERTIES OF 68.0 kg.(150 lb.) TDNiCr UNITS

Heat No.	Gauge cm.	Room Temperature UTS MN/m^2	YS MN/m^2	Elong. % cm.	1093°C UTS MN/m^2	YS MN/m^2	Elong. % cm.	Stress Rupture 1093°C 31.1 MN/m^2	38.0 MN/m^2
3519	0.038	789.6	520.2	20.0	101.3	101.3	4.5	>20 hrs.	
3520	0.025	764.8	507.8	13.8	119.2	119.2	2.5	>20 hrs.	
	0.038	742.7	497.6	20.0	121.3	121.3	5.5	>20 hrs.	
3521	0.025	705.5	486.4	20.0	100.5	100.5	1.1	>20 hrs.	
3522	0.025	775.8	531.2	15.5	129.5	129.5	1.6	>20 hrs.	
3523	0.025	771.0	655.9	19.6	108.2	108.2	3.0	>20 hrs.	
	0.043	766.2	498.8	24.0	122.6	122.6	3.0	>20 hrs.	
	0.089	779.3	507.1	22.5	133.0	133.0	3.0		>20 hrs.
3524	0.025	756.5	515.4	17.5	119.2	119.2	2.5	>20 hrs.	
3525	0.025	689.0	464.4	20.9	108.2	108.2	1.7	>20 hrs.	
3526	0.025	691.8	465.1	20.0	84.1	84.1	1.2	>20 hrs.	
3528	0.025	809.6	533.3	23.6	124.0	124.0	1.9	>20 hrs.	

TABLE 69

MECHANICAL PROPERTIES OF 68.0 kg.(150 lb.) TDNiCr UNITS

Heat No.	Gauge in.	Room Temperature UTS ksi	Room Temperature YS ksi	Room Temperature Elong. %- n.	2000°F UTS ksi	2000°F YS ksi	2000°F Elong. %-in.	Stress Rupture 2000°F 4500 psi	Stress Rupture 2000°F 5500 psi
3519	0.015	114.6	75.5	20.0	14.7	14.7	4.5	>20 hrs.	
3520	0.010	111.0	88.2	13.8	17.3	17.3	2.5	>20 hrs.	
	0.015	107.8	72.2	20.0	17.6	17.6	5.5	>20 hrs.	
3521	0.010	102.4	70.6	20.0	14.6	14.6	1.1	>20 hrs.	
3522	0.010	112.6	77.1	15.5	18.8	18.8	1.6	>20 hrs.	
3523	0.010	111.9	95.2	19.6	15.7	15.7	3.0	>20 hrs.	
	0.017	111.2	72.4	24.0	17.8	17.8	3.0	>20 hrs.	
	0.035	113.1	73.6	22.5	19.3	19.3	3.0		>20 hrs.
3524	0.010	109.8	74.8	17.5	17.3	17.3	2.5	>20 hrs.	
3525	0.010	100.0	67.4	20.9	15.7	15.7	1.7	>20 hrs.	
3526	0.010	100.4	67.5	20.0	12.2	12.2	1.2	>20 hrs.	
3528	0.010	117.5	77.4	23.6	18.0	18.0	1.9	>20 hrs.	

Typical "as-consolidated-hot rolled" 2.54 cm. (1.0 in.) slabs fabricated by the alternate consolidation procedure are shown in Figure 72. Extent of edge and end cracking may be noted.

Yield data at the 2.54 cm. (1.0 in.) slab stage after conditioning are shown in Table 70 for the seven units fabricated by the alternate consolidation procedure. As indicated, yields varied from a low of 46.5 percent to a high of 74.1 percent. The overall average yield was calculated to be 60.3 percent. While this yield was less than that attained for the units fabricated by the conventional consolidation (62.1 percent), the difference was believed to be insignificant. It should, however, be pointed out that standard consolidation procedures yielded more consistent results than alternate procedures.

During this same period of time, a series of thirteen additional 68.0 kg. (150 lb.) units were compacted by standard procedures. Subsequently, these units were canned in conventional roll consolidation cans as shown in Figure 14 and subjected to a combination sinter-roll consolidation preheat in the Pereny Sinter-Consolidation Furnace. The alternate consolidation procedure was then employed to fabricate the units to the 2.54 cm. (1.0 in.) slab stage of processing. Resultant post-condition yields were determined as shown in Table 71. Again, it was noted that the alternate consolidation procedure resulted in quite variable yields. The spread encountered was a low of 32 percent and a high of 62.2 percent.



FIGURE 72

TYPICAL 68.0 kg.(150.0 lb.) TDNiCr UNITS
FABRICATED BY ALTERNATE CONSOLIDATION PROCEDURES

TABLE 70

YIELD DATA FOR 68.0 kg. (150 lb.) TDNiCr UNITS FABRICATED BY ALTERNATE CONSOLIDATION PROCEDURE

Heat No.	2.54 cm. (1 in.) Slab Stage						% Yield
	cm.			in.			
	T	W	L	T	W	L	
3688	2.37	73.66	26.35	0.938	29	10-3/8	51.0
3689	2.39	69.85	25.72	0.943	27-1/2	10-1/8	53.2
3691	2.37	72.39	31.11	0.938	28-1/2	12-1/4	65.1
3692	2.75	67.31	33.18	1.085	26-1/2	13-1/16	74.1
3693	2.42	73.98	28.57	0.955	29-1/8	11-1/4	63.0
3694	2.32	73.66	30.48	0.917	29	12	69.5
3696	2.42	66.36	23.18	0.955	26-1/8	9-1/8	46.5

TABLE 71

YIELD DATA FOR 68.0 kg. (150 lb.) TDNiCr UNITS FABRICATED BY ALTERNATE SINTER-CONSOLIDATION PROCEDURE

Heat No.	2.54 cm.(1 in.) Slab Stage						% Yield
	cm.			in.			
	T	W	L	T	W	L	
3690	2.01	76.83	23.49	0.785	30-1/4	9-1/4	48.5
3695	2.34	78.90	25.88	0.920	31-1/16	10-3/16	58.0
3697	2.24	71.12	25.24	0.876	28	9-15/16	46.6
3698	2.29	76.52	28.10	0.900	30-1/8	11-1/16	61.1
3699	2.49	77.79	27.62	0.980	30-5/8	10-7/8	62.2
3700	1.93	73.34	25.50	0.760	28-7/8	10	44.5
3701	2.24	79.06	26.67	0.880	31-1/8	10-1/2	56.2
3702	2.12	78.74	28.26	0.835	31	11-1/8	58.0
3703	1.97	73.34	24.61	0.775	28-7/8	9-11/16	46.5
3704	2.17	30.80	30.48	0.857	12-1/8	12	50.0
3704	2.17	44.13	26.99	0.857	17-3/8	10-5/8	
3705	2.23	76.20	23.81	0.875	30	9-3/8	51.5
3706	2.17	73.98	16.19	0.855	29-1/8	6-3/8	32.0
3707	2.38	73.34	21.91	0.938	28-7/8	8-5/8	45.0

The overall yield was found to be 57.7 percent which also was lower than 68.0 kg. (150 lb.) units consolidated by conventional methods.

Therefore, it was concluded that roll consolidation of the 68.0 kg. (150 lb.) units should be carried out by conventional methods to obtain the greatest possible yield at the 2.54 cm. (1.0 in.) slab thickness. Further, the effect upon yield of the combination sinter-consolidation procedure will have to be determined on a future run using the conventional consolidation technique in conjunction with the sinter-consolidation furnace.

All twenty units described above (Heat 3688 through 3707) were subsequently canned and warm rolled from the 2.54 cm. (1.0 in.) thickness to the intermediate plate stage thickness. Since the widths of these units were larger than ever rolled before, it was necessary to utilize the new Trent Warm Rolling Oven in conjunction with the Schloemann Mill for breakdown rolling. During this stage of processing certain handling difficulties were encountered by the rollers and techniques had to be developed in order to facilitate removal of the units from the furnace, reduce time expended in movement of the unit to the rolling mill and determination of roll pass schedules to satisfy requirements of the increased unit widths.

It was believed that a combination of the above-mentioned factors was the cause of certain of these heats failing to satisfy the 3T bend requirement during testing

at final gauge sheet of 0.025 to 0.102 cm. (0.010 to 0.040 in.) thick. Properties other than bends were found to be satisfactory in all cases.

6. Specification Goals

The process improvement studies conducted during the Part I phase of this contract were directed toward achieving a number of specification goals for TDNiCr sheet; these are shown in Table 72. Tentative Specification requirements have been developed from the data from Part I and are also listed in Table 72. The derivation of these requirements is given in the following paragraphs.

a. Chemical Composition

As indicated during the reproducibility evaluation detailed in Section I-3 of this report, chemical compositions were well within Fansteel Specification Requirements and also satisfied goal specification requirements. However, the reproducibility evaluation consisted of only three heats. A similar evaluation of fifty-nine heats utilized for production of TDNiCr sheet indicated that again, all chemical compositions were well within Fansteel Specification Requirements, but certain modifications to the specification goals would be recommended based upon the results.

The chromium contents of the fifty-nine production heats were found to range from 18.40 to 20.21 percent in comparison to a specification goal of 19.00 to 21.00 percent, while the actual range experienced was tighter than the range specified by the goal, a shift downward in chromium content

TABLE 72

SPECIFICATION GOALS

Test Category	Goals Part I	Tentative Specification
Chemical Composition		
Cr	19.00-21.00%	18.50-20.50%
C	0.03% Max.	0.05% Max.
S	0.01% Max.	0.01% Max.
ThO_2	1.80-2.60%	1.80-2.60%
Mechanical Properties		
0.051-0.102 cm. (0.020-0.040 in.) Sheet		
Room Temp. U.T.S.	767.9 MN/m^2(110.0 ksi)	767.9 MN/m^2(110.0 ksi)
Y.S.	516.8 MN/m^2(75.0 ksi)	516.8 MN/m^2(75.0 ksi)
El. %	15	10
0.025-<0.051 cm. (0.010-<0.020 in.) Sheet		
Room Temp. U.T.S.	767.9 MN/m^2(110.0 ksi)	689.0 MN/m^2(100.0 ksi)
Y.S.	516.8 MN/m^2(75.0 ksi)	447.9 MN/m^2(65.0 ksi)
El. %	10	10
0.051-0.102 cm. (0.020-0.040 in.) Sheet		
1093°C(2000°F) U.T.S.	103.4 MN/m^2(15.0 ksi)	103.4 MN/m^2(15.0 ksi)
Y.S.	To be reported	To be reported
El. %	2	2
0.025-<0.051 cm. (0.010-<0.020 in.) Sheet		
1093°C(2000°F) U.T.S.	82.7 MN/m^2(12.0 ksi)	68.9 MN/m^2(10.0 ksi)
Y.S.	To be reported	To be reported
El. %	2	1
0.051-0.102 cm. (0.020-0.040 in.) Sheet		
Stress Rupture 1093°C(2000°F)	37.9 MN/m^2(5.5 ksi)-20 hrs. and 34.5 MN/m^2(5.0 ksi)-100 hrs.	37.9 MN/m^2(5.5 ksi)-20 hrs.

TABLE 72
(CONT'D)

SPECIFICATION GOALS

Test Category	Goals Part I	Tentative Specification
Mechanical Properties (cont'd)		
0.025-<0.051 cm. (0.010-<0.020 in.) Sheet		
Stress Rupture (1093°C(2000°F)	31.0 MN/m^2(4.5 ksi) 20 hrs. 27.6 MN/m^2(4.0 ksi) 100 hrs.	31.0 MN/m^2(4.5 ksi) 20 hrs.
Bend Test	2.0T - 105°	3.0T - 105°
Thickness Tolerance		
0.0127-0.0229 cm. (0.005-0.009 in.)	±10% ±10%	±10% ±10%
0.025-<0.051 cm. (0.010-<0.020 in.)	±10% ±10%	±10% ±10%
0.051-<0.089 cm. (0.020-<0.035 in.)	±0.0051 cm. (±0.002 in.)	±10% ±10%
0.089-<0.145 cm. (0.035-<0.057 in.)	±0.0076 cm. (±0.003 in.)	±0.0102 cm. (±0.004 in.)
Weight Tolerance	+5% Max.	+5% Max.
Flatness	6%	6%
Surface Finish	16 rms Max.	32 rms Max.

was encountered. Since this shift did not appear to have any detrimental effects upon mechanical properties, it is recommended that the proposed goal chromium content be changed from 19.00-21.00 percent to 18.50 to 20.50 percent.

Carbon contents of the fifty-nine production heats were found in certain instances to exceed a specification goal content of 0.03 percent. Since no adverse effect upon mechanical properties was encountered, a more realistic goal of 0.05 percent maximum carbon content is recommended.

Sulfur and thoria contents for both the reproducibility evaluation and fifty-nine production heats were found to satisfy Fansteel Specification Requirements as well as goal specification. Therefore no changes are recommended.

b. Mechanical Properties

(1.) Room Temperature Tensile Properties

Evaluation of room temperature tensile properties of both reproducibility and production heats indicated that a specification goal of 15 percent elongation for 0.051-0.102 cm. (0.020-0.040 in.) sheet was satisfied in all cases except one test of 0.038 cm. (0.015 in.) sheet which yielded an elongation of 12.5 percent. Also, a number of heats yielded elongations falling right at the minimum value of 15 percent. It is therefore recommended that the goal specification be modified to a 10 percent value.

Results obtained on 0.025 cm. (0.010 in.) sheet indicated that a goal value of 10 percent elongation was satisfactory. However, a room temperature yield strength

goal of 516.8 MN/m^2 (75,000 psi) was unsatisfactory since approximately 50 percent of the 0.025 cm. (0.010 in.) heats yielded lower test results. In addition, a room temperature ultimate tensile strength goal requirement of 757.9 MN/m^2 (110,000 psi) was also believed high for the 0.025 cm. (0.010 in.) sheet since again approximately 50 percent of the test results fell below the goal requirement. Therefore, recommended values for room temperature ultimate tensile strength and yield strength of 0.025 cm. (0.010 in.) sheet is 689.0 MN/m^2 (100,000 psi) and 447.9 MN/m^2 (65,000 psi).

(2.) Elevated Temperature Tensile Properties

Elevated temperature tensile property goal requirements for the 0.051-0.102 cm. (0.020-0.040 in.) appear quite feasible according to evaluation results. However, the ultimate tensile strength goal for the 0.025 cm. (0.010 in.) sheet of 82.7 MN/m^2 (12,000 psi) should be reduced to 68.9 MN/m^2 (10,000 psi) and the 2 percent elongation should be reduced to 1 percent.

(3.) Stress-Rupture 1093°C(2000°F) in Air

Goal requirements for 1093°C(2000°F) air stress rupture testing were handily satisfied for all 0.025-0.102 cm. (0.010-0.040 in.) sheet evaluated.

(4.) Bend Testing

Predicated on the results yielded from the Part I contract reproducibility and production sheet test evaluation, a minimum feasible bend requirement appears to require a bend factor (radius) of 3.0. The goal requirement of a 2.0 bend

factor (radius) seems to be marginal for 0.025-0.102 cm. (0.010-0.040 in.) sheet.

c. Dimensional and Weight Tolerances

Reviewing the data presented on the reproducibility evaluation in Section I-3 of this report, it was pointed out that no difficulty was encountered in satisfying goal requirements for dimensional and weight tolerances for sheet 0.051 cm. (0.020 in.) or greater in thickness, but sheet of 0.025 cm. (0.010 in.) in thickness required greater control during processing. It was found that tension cold roll finishing was necessary to satisfy all tolerance requirements. This conclusion was verified by production sheet produced subsequent to the reproducibility run.

d. Flatness

A goal flatness requirement of 6 percent could be achieved by use of roll leveling on sheets of 0.051 cm. (0.020 in.) or greater in thickness.

For all sheet thicknesses less than 0.051 cm. (0.020 in.), but greater than 0.025 cm. (0.010 in.) inclusive, it was necessary to employ tension cold roll finishing to achieve flatness satisfying goal requirements.

e. Surface Finish

In all cases a surface finish of 32 rms was obtained by either abrasive grinding or cold roll finishing. In order to attain a 16 rms finish or better additional labor in the form of extra polishing would be required in all cases. If a finish of this type is required, it may readily be attained.

f. Product Yield

As reported in Section I-4 of this report, production TDNiCr sheet was shown to have yields per gauge as follows:

Gauge	% Yield
0.025 cm. (0.010 in.)	35.4
0.038-0.051 cm. (0.015-0.020 in.)	36.1
0.076 cm. (0.030 in.)	43.8

In summary, the aforementioned data were employed in the preparation of a goal product specification for future work to be carried out during the Part II program.

g. Specifications for Production TDNiCr Sheet

Based upon the data generated during the Part I program, it is recommended that any production TDNiCr sheet produced during the Part II program, shall be certified to satisfy Fansteel Specifications S-TC-S-01-R-1 and S-DMM-S-01-R-0.

At the conclusion of the Part II program, the Fansteel Specifications may be modified to reflect changes deemed necessary as a result of test data and/or process changes developed during Parts I and II of the program.

PRECEDING PAGE BLANK NOT FILMED

III - ALLOY STUDIES

1. Program Requirements

Alloy composition studies were planned to seek improvements in performance over that of the nominal composition alloy, Ni-20%Cr-2%ThO_2. Three areas were to be explored:

- Optimization of the nominal basic alloy composition, Ni-20Cr-2ThO_2 and reevaluate the specification limits.
- Evaluate the effect of small element additions upon both the low temperature and the high temperature ductility values.
- Study the effect of alloy additions on the oxidation and erosion resistance of the Ni-20Cr-2ThO_2 alloy.

2. Alloy Composition Optimization

The Fansteel Specification defines the composition of TDNiCr as:

ThO_2	1.5 to 3.0%
Chromium	18.0 to 22.0%

These ranges will be narrowed ---- the goal range being:

ThO_2	1.8 to 2.6%
Chromium	19.0 to 21.0%

An examination of data from 22 heats of TDNiCr manufactured during the year preceding the initiation of the contract showed no mechanical property variations attributable to composition differences in the following ranges:

ThO_2	1.9 to 3.0%
Chromium	19.9 to 21.5%

Preceding page blank

To confirm the production scale results and establish an optimum NiCr ThO_2 base composition a compositional variation study was conducted at 4.54 kg. (10 lb.) unit scale. The aim compositions encompassed only the limits of the specification because of the previously small demonstrated effects of compositional variation:

Ni 17Cr 1.5ThO_2

Ni 17Cr 3.0ThO_2

Ni 20Cr 2.0ThO_2

Ni 23Cr 1.5ThO_2

Ni 23Cr 3.0ThO_2

Powder was manufactured by standard techniques in small scale equipment. A 9.07 kg. (20 lb.) lot of each nominal composition was produced and compacted into two 4.54 kg. (10 lb.) units. Each was sintered and forged using the temperature schedules, Figure 1, used for production TDNiCr units. After forging and decanning, slabs were conditioned and recanned for rolling using standard practices. Rolling to 0.076 cm. and 0.025 cm. (0.030 and 0.010 in.) gauges was done under standard conditions of rolling temperature and can configuration. The rolled sheets were decanned, cleaned of surface oxide and heat treated by a standard cycle. Evaluation of the heat treated sheet included room temperature and 1093°C(2000°F) tensile and 1093°C(2000°F) stress rupture testing and room temperature bend tests.

Samples of each sheet were also exposed to a 0.1 Torr vacuum environment at 1204°C(2200°F) for 100 one-hour cycles (cycle was 55 minutes heating, 5 minutes cooling). Subsequent evaluation included 1093°C(2000°F) tensile and stress rupture testing and microstructural examination.

The compositions varied from the nominal aims; ThO_2 ranging from 1.8 to 3.9% and chromium from 16.2 to 22.3%. The deviations are attributed to variations in yields of the various components in the pilot-plant scale powder-making equipment.

Within the actual composition ranges studied, the variations observed in properties could not be correlated with composition. The test data were similar to those produced previously for standard TDNiCr sheet. A higher degree of variation was encountered, but this is expected with small scale test data.

Yield considerations call for the elimination of alloys containing ThO_2 in excess of 3.0% ThO_2.

These data reinforced the previous Fansteel data on the effect of composition. The presently constituted specification limits of:

ThO_2	1.5-3.0%
Chromium	18.0-22.0%

will be maintained.

The goal compositions which would narrow the ranges will also be maintained:

ThO_2	1.8-2.6%
Chromium	19.0-21.0%

3. Ductility Improvement

The ductility of dispersion strengthened alloys is reduced over the whole temperature spectrum by the introduction of the dispersoid particles. A series of minor alloy changes have been made in an effort to regain part of the inherent ductility of the nickel-chromium matrix composition.

Improvements in ductility of TDNiCr were sought by three techniques:

- Reduction in the ThO_2 content.
- Reduction in the size and content of Cr_2O_3 particles.
- Reduction in tramp element and interstitial content.

The goal was 20 percent elongation at room temperature and 5 percent elongation at 1093°C(2000°F) without significant impairment of other properties.

a. Scouting Studies

(1.) Low ThO_2 Content Study

Small scale 4.54 kg. (10 lb.) bars of the following compositions were evaluated:

Ni-20Cr-0.5 ThO_2

-1.0 ThO_2

-1.5 ThO_2

The sheet bars were processed to 0.038 cm. (0.015 in.) sheet for evaluation.

(2.) Extended Sintering Cycle Study

Subsequent to canning, a 4.54 kg. (10 lb.) unit of Ni-20Cr-2ThO_2 was subjected to an extended hydrogen

sintering cycle in an effort to remove most of the excess oxygen and any tramp elements of relatively high vapor pressure. The cycle consisted of 50 hours at 1121°C(2050°F) and would be expected to minimize the formation of Cr_2O_3.

The sheet bar was processed to 0.038 cm. (0.015 in.) sheet for evaluation.

(3.) Alloy Additions

Since minor additions of reactive elements should aid in tying up residual S, N, C and O, the elements Th, La, Y, Hf, Zr, Ti, Si, Mg and Al were added to the base Ni-20Cr-2ThO_2 composition at levels sufficient to react with 0.1 and 0.2 percent excess O, the major contaminant. It was estimated that these levels represented stoichiometry and twice stoichiometry for the O reaction, respectively.

The sheet bars were processed to 0.038 cm. (0.015 in.) sheet for evaluation.

(4.) Metal Hydride Study

One method of oxygen removal is through the decomposition of a metal hydride with the liberated nascent hydrogen acting as a potent reducing agent. Therefore, four 4.54 kg. (10 lb.) units were evaluated utilizing 0.05 and 0.1 percent additions of both CaH_2 and LiH. A 954°C(1750°F) sintering cycle was utilized in each case as no untoward outgassing was noted in processing.

(5.) Halide Study

Another means for removing excess oxygen is through the use of a volatile halide. Three 4.54 kg. (10 lb.)

units were evaluated utilizing 0.1 percent additions of NH_4Cl, NH_4I and NH_4F to the powder prior to canning for the forging operation. A standard sintering operation was utilized.

Sheet bars were processed to 0.038 cm. (0.015 in.) sheet for evaluation.

b. Results of Ductility Scouting Studies

Table 73 is a list of the modified TDNiCr alloys which were successfully processed to 0.038 cm. (0.015 in.) sheet. The processing was similar for each of the billets. The 4.54 kg. (10 lb.) units were rolled to sheet for evaluation. Table 74 is a compilation of the mechanical properties derived from tensile and bend specimens fabricated from the sheet stock. Figure 73 shows the typical microstructures which were derived.

Promising overall performance was obtained through the hydride additions. High elevated tensile elongation, high strength and good bend ductility were observed in each case.

The halide additions afforded clean microstructures; however, all three heats revealed a fine grain size, and hence low, elevated temperature strength.

The reactive element additions did not, in general, afford any substantial improvement over that for standard TDNiCr sheet. In fact, rare earth additions lowered bend ductility.

TABLE 73

CHEMICAL ANALYSES MODIFIED TDNiCr ALLOYS

HEAT NO.	NOMINAL COMPOSITION	ANALYZED COMPOSITION
3333	Ni-20Cr-0.5ThO_2	Ni-24Cr-0.5ThO_2
3334	Ni-20Cr-1.0ThO_2	Ni-17Cr-1.0ThO_2
*3343	Ni-20Cr-2ThO_2	Ni-19Cr-2.2ThO_2
3364	Ni-20Cr-2ThO_2(0.05LiH)	Ni-20Cr-0.02Li-2.2ThO_2
3365	Ni-20Cr-2ThO_2(0.01LiH)	Ni-18Cr-0.01Li-2.2ThO_2
3366	Ni-20Cr-2ThO_2(0.1LiH)	Ni-19Cr-0.09Li-2.2ThO_2
3367	Ni-20Cr-2ThO_2(0.05CaH_2)	Ni-19Cr-0.02Ca-2.1ThO_2
3368	Ni-20Cr-2ThO_2(0.1CaH_2)	Ni-19Cr-0.09Ca-2.2ThO_2
3369	Ni-20Cr-2ThO_2(0.1NH_4Cl)	Ni-19Cr-2.1ThO_2
3370	Ni-20Cr-2ThO_2(0.1NH_5F)	Ni-19Cr-2.1ThO_2
3371	Ni-20Cr-2ThO_2(0.1NH_4I)	Ni-18Cr-2.1ThO_2
3407	Ni-20Cr-0.6Hf-2ThO_2	Ni-17Cr-0.6Hf-2.2ThO_2
3408	Ni-20Cr-1.2Hf-2ThO_2	Ni-17Cr-1.1Hf-2.2ThO_2
3411	Ni-20Cr-1.5ThO_2	Ni-21Cr-1.75ThO_2
3420	Ni-20Cr-0.3Zr-2ThO_2	Ni-18Cr-0.3Zr-2.3ThO_2
3431	Ni-20Cr-0.15Ti-2ThO_2	Ni-20Cr-0.12Ti-2.3ThO_2
3427	Ni-20Cr-0.3Ti-2ThO_2	Ni-19Cr-0.25Ti-2.3ThO_2
3428	Ni-20Cr-0.2Si-2ThO_2	Ni-21Cr-0.2Si-2.2ThO_2
3432	Ni-20Cr-0.1Si-2ThO_2	Ni-19Cr-0.3Si-2.4ThO_2
3433	Ni-20Cr-0.3Mg-2ThO_2	Ni-19Cr-0.01Mg-2.2ThO_2
3448	Ni-20Cr-0.1Al-2ThO_2	Ni-20Cr-0.1Al-2.2ThO_2
3449	Ni-20Cr-0.2Al-2ThO_2	Ni-19Cr-0.2Al-2.1ThO_2
3450	Ni-20Cr-0.6Y-2ThO_2	Ni-19Cr-0.4Y-2.2ThO_2
3459	Ni-20Cr-0.7Th-2ThO_2	Ni-19Cr-0.7Th-2.3ThO_2
3460	Ni-20Cr-1.4Th-2ThO_2	Ni-18Cr-1.4Th-2.3ThO_2
3461	Ni-20Cr-1.2La-2ThO_2	Ni-19Cr-1.0La-2.2ThO_2
3462	Ni-20Cr-0.3Y-2ThO_2	Ni-19Cr-0.3Y-2.2ThO_2

*Sintered 50 hours at 1121°C(2050°F)

TABLE 74

MECHANICAL PROPERTIES OF MODIFIED TDNiCr ALLOYS

Heat No.	Nominal Composition	Room Temperature UTS MN/m^2	Room Temperature YS MN/m^2	Room Temperature Elong. %	1093°C UTS MN/m^2	1093°C YS MN/m^2	1093°C Elong. %	1093°C 4500 S/R Hrs.	Trans. Bend Radius 105°
3333	Ni-20Cr-0.5ThO_2	845.9	724.6	24.0	74.4	64.8	16.0	Failed on Loading	1.3T
3334	Ni-20Cr-1.0ThO_2	779.1	649.4	30.0	103.4	103.4	11.0	>20	1.3T
3411	Ni-20Cr-1.5ThO_2	892.8	720.5	30.0	113.0	113.0	5.0	>20	2T
*3343	Ni-20Cr-2ThO_2	897.0	699.8	21.0	79.2	67.5	9.0	0.1	2T
3364	Ni-20Cr-2ThO_2(0.05LiH)	992.8	772.2	20.0	149.6	149.6	9.0	>20	3T
3365	Ni-20Cr-2ThO_2(0.01LiH)	928.0	723.2	20.0	115.1	103.4	10.0	>20	3T
3366	Ni-20Cr-2ThO_2(0.1 LiH)	908.7	661.9	21.0	128.2	128.2	12.0	>20	3T
3367	Ni-20Cr-2ThO_2(0.05CaH_2)	852.1	618.4	25.0	127.5	125.4	12.0	>20	3T
3368	Ni-20Cr-2ThO_2(0.1CaH_2)	923.9	692.9	17.0	127.5	126.1	7.0	>20	3T
3369	Ni-20Cr-2ThO_2(0.1NH_4Cl)	862.5	652.9	30.0	61.3	61.3	12.0	0.7	3T
3370	Ni-20Cr-2ThO_2(0.1NH_4F)	884.6	679.8	26.0	62.0	62.0	10.0	0.2	2T
3371	Ni-20Cr-2ThO_2(0.1 NH_4I)	792.2	642.5	15.0	27.5	-	9.0	Failed on Loading	3T
3407	Ni-20Cr-0.6Hf-2ThO_2	505.3	431.6	10.0	88.2	84.1	4.0	>20	7T
3408	Ni-20Cr-1.2Hf-2ThO_2	957.6	734.9	18.0	162.0	160.6	4.0	>20	>4T
3420	Ni-20Cr-0.3Zr-2ThO_2	899.7	653.6	25.0	149.6	131.6	9.0	>20	4T
3427	Ni-20Cr-0.3Ti-2ThO_2	882.5	649.4	28.0	110.3	110.3	6.0	>20	2T
3432	Ni-20Cr-0.1Si-2ThO_2	999.2	785.3	15.0	135.1	135.1	8.0	>20	3T
3433	Ni-20Cr-0.3Mg-2ThO_2	979.0	842.5	18.0	137.8	127.6	6.4	>20	4T

*Long term H_2 sinter, 50 hours at 1121°C

TABLE 74

MECHANICAL PROPERTIES OF MODIFIED TDNiCr ALLOYS

Heat No.	Nominal Composition	Room Temperature UTS ksi	Room Temperature YS ksi	Room Temperature Elong. %	2000°F UTS ksi	2000°F YS ksi	2000°F Elong. %	2000°F 4500 S/R Hrs.	Trans. Bend Radius 105°
3333	Ni-20Cr-0.5ThO_2	122.7	105.1	24.0	10.8	9.4	16.0	Failed on Loading	1.3T
3334	Ni-20Cr-1.0ThO_2	113.0	94.2	30.0	15.0	15.0	11.0	>20	1.3T
3411	Ni-20Cr-1.5ThO_2	129.5	104.5	30.0	16.4	16.4	5.0	>20	2T
*3343	Ni-20Cr-2ThO_2	130.1	95.7	21.0	11.5	9.8	9.0	0.1	2T
3364	Ni-20Cr-2ThO_2(0.05LiH)	144.0	112.0	20.0	21.7	21.7	9.0	>20	3T
3365	Ni-20Cr-2ThO_2(0.01LiH)	134.6	104.9	20.0	16.7	15.0	10.0	>20	3T
3366	Ni-20Cr-2ThO_2(0.1LiH)	131.8	96.0	21.0	18.6	18.6	12.0	>20	3T
3367	Ni-20Cr-2ThO_2(0.05CaH_2)	123.6	89.7	25.0	18.5	18.2	12.0	>20	3T
3368	Ni-20Cr-2ThO_2(0.1CaH_2)	134.0	100.5	17.0	18.5	18.3	7.0	>20	3T
3369	Ni-20Cr-2ThO_2(0.1NH_4Cl)	125.1	94.7	30.0	8.9	8.9	12.0	0.7	3T
3370	Ni-20Cr-2ThO_2(0.1NH_4F)	128.3	98.6	26.0	9.0	9.0	10.0	0.2	2T
3371	Ni-20Cr-2ThO_2(0.1NH_4I)	114.9	93.2	15.0	4.0	-	9.0	Failed on Loading	3T
3407	Ni-20Cr-0.6Hf-2ThO_2	73.3	62.6	10.0	12.8	12.2	4.0	>20	7T
3408	Ni-20Cr-1.2Hf-2ThO_2	138.9	106.6	18.0	23.5	23.3	4.0	>20	>4T
3420	Ni-20Cr-0.3Zr-2ThO_2	130.5	94.8	25.0	21.7	19.1	9.0	>20	4T
3427	Ni-20Cr-0.3Ti-2ThO_2	128.0	94.2	28.0	16.0	16.0	6.0	>20	2T
3432	Ni-20Cr-0.1Si-2ThO_2	144.9	113.9	15.0	19.6	19.6	8.0	>20	4T
3433	Ni-20Cr-0.3Mg-2ThO_2	142.0	122.2	18.0	20.0	18.5	6.4	>20	4T

*Long term H_2 sinter, 50 hours at 2050°F

TABLE 74 (Cont'd)

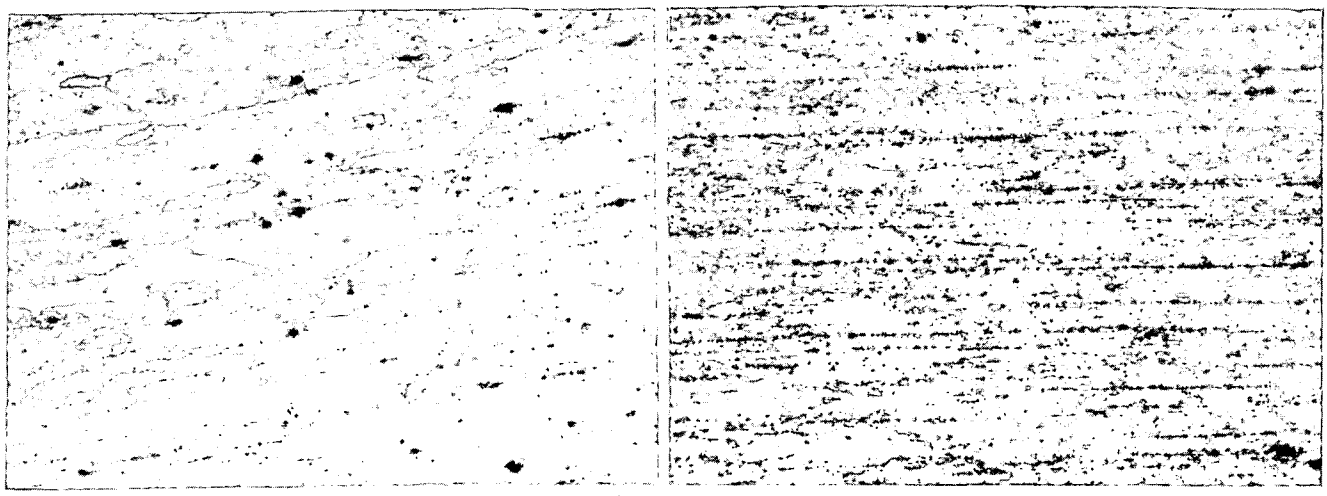
MECHANICAL PROPERTIES OF MODIFIED TDNiCr ALLOYS

Heat No.	Nominal Composition	Room Temperature UTS MN/m^2	Room Temperature YS MN/m^2	Room Temperature Elong. %	1093°C UTS MN/m^2	1093°C YS MN/m^2	1093°C Elong. %	1093°C 4500 S/R Hrs.	Trans. Bend Radius 105°
3448	Ni-20Cr-0.1Al-2ThO_2	978.3	862.6	20.0	140.5	140.5	7.2	>20	5T
3449	Ni-20Cr-0.2Al-2ThO_2	923.9	793.7	25.0	146.8	146.8	6.2	>20	2T
3450	Ni-20Cr-0.6Y-2ThO_2	923.2	692.4	20.0	126.2	105.4	10.0	>20	6T
3459	Ni-20Cr-1.4Th-2ThO_2	930.8	745.4	25.0	146.8	145.4	12.0	>20	8T
3461	Ni-20Cr-1.2La-2ThO_2	932.2	805.4	22.0	155.8	155.8	8.8	>20	9T
3462	Ni-20Cr-0.3Y-2ThO_2	984.5	757.2	20.0	153.0	153.0	8.8	>20	5T

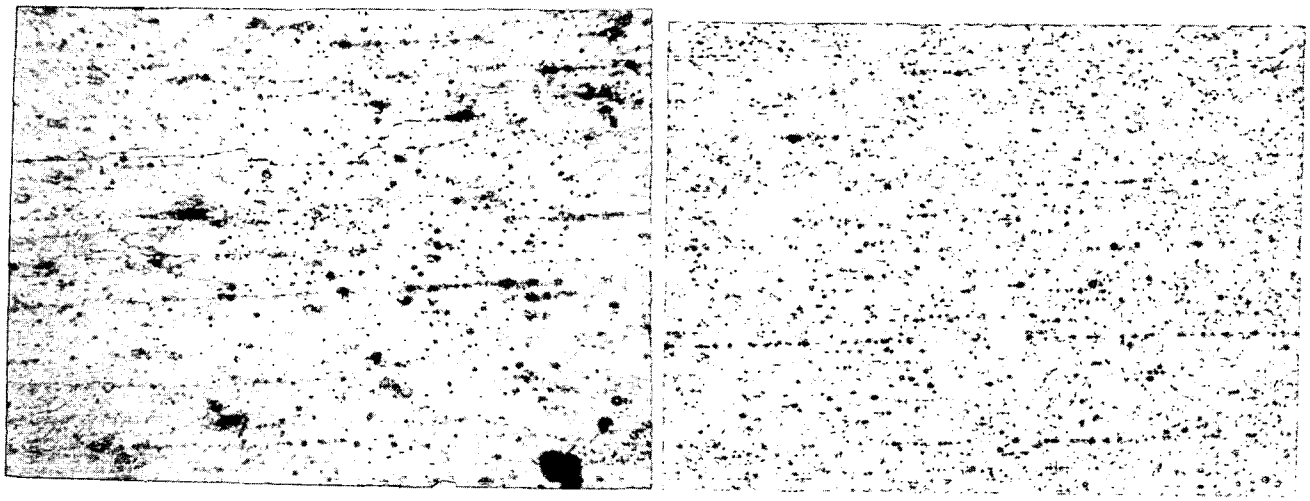
TABLE 74 (Cont'd)

MECHANICAL PROPERTIES OF MODIFIED TDNiCr ALLOYS

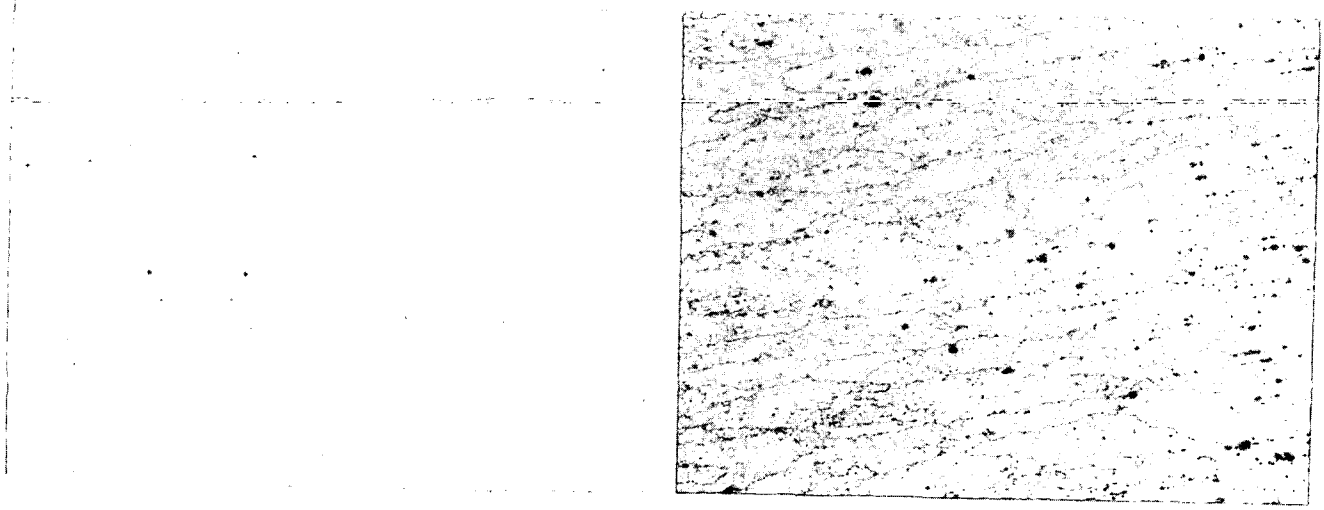
Heat No.	Nominal Composition	Room Temperature UTS ksi	Room Temperature YS ksi	Room Temperature Elong. %	2000°F UTS ksi	2000°F YS ksi	2000°F Elong.	2000°F 4500 S/R Hrs.	Trans. Bend Radius 105°
3448	Ni-20Cr-0.1Al-2ThO_2	141.9	125.2	20.0	20.4	20.4	7.2	>20	5T
3449	Ni-20Cr-0.2Al-2ThO_2	137.3	115.2	25.0	21.3	21.3	6.2	>20	2T
3450	Ni-20Cr-0.6Y-2ThO_2	134.0	100.5	20.0	18.3	15.3	10.0	>20	6T
3459	Ni-20Cr-1.4Th-2ThO_2	135.1	108.2	25.0	21.3	21.1	12.0	>20	8T
3461	Ni-20Cr-1.2La-2ThO_2	135.3	116.9	22.0	22.6	22.6	8.8	>20	9T
3462	Ni-20Cr-0.3Y-2ThO_2	142.9	109.9	20.0	22.2	22.2	8.8	>20	5T



Heat 3411(Typical TDNiCr Structure) Heat 3365 (Hydride Addition)



Heat 3459 (Rare Earth Addition) Heat 3343 (Long Term Sinter)



Heat 3371 (Halide Addition As Polished) Heat 3427 (Reactive Element Addition)

FIGURE 73

Representative Microstructures of Modified TDNiCr Alloys x250

Decreasing ThO_2 contents resulted in increased ductility but decreased strength. Since the strength loss was not very great down to 1.0T ThO_2, these alloys were selected for further work at a larger scale.

The long term sinter experiment (Heat 3343) resulted in a material of fine grain size and performed similarly to the sheet stock to which halide additions were made.

4. Oxidation Improvement

a. Program

When TDNiCr is exposed to air at elevated temperatures the oxidation products and kinetics are chiefly a function of temperature, time, gas velocity, angle of impingement, stress, total dynamic pressure and substrate grain size and morphology. Since standard TDNiCr may not have the desired oxidation resistance over the whole temperature range from 982°C to 1204°C (1800°F to 2200°F) for space shuttle application, this portion of the program was aimed at modifying the base composition to further improve its oxidation resistance without seriously impairing other requisite properties.

At the program's inception it was generally believed that the major detriment to the performance of TDNiCr was the conversion of the protective oxide, Cr_2O_3, to CrO_3 gas. Under space shuttle conditions some early estimates of the rate of this reaction precluded the use of TDNiCr at a temperature of 1204°C(2200°F). Performance at 1204°C(2200°F) under space shuttle conditions was therefore chosen as the basis for the selection of the alloy systems to be evaluated.

One approach taken was to alloy the TDNiCr with elements that tend to form complex oxides or spinels with Cr_2O_3. Of major interest here were additions of Mn and Fe which showed promise in some earlier work. Si had been found to be of further benefit when used in conjunction with these additives owing to the formation of a sub-scale of SiO_2. In addition, La has been thought to stabilize MN Cr_2O_4 in alloys such as Rene' Y and was included in the study.

A second approach was that of utilizing a minimum of 3 percent Al in the nickel-chromium alloy matrix. In this manner, it was expected that Cr_2O_3 formation would be greatly suppressed in favor of the non-volatile Al_2O_3 and $NiAl_2O_4$ species.

b. Test Procedure

Three matrix compositions were studied: Ni-16Cr, Ni-20Cr and Ni-30Cr. Rare earth additions including Y, La and Th were included in the investigation, chiefly in combination with Al since these elements have been thought to promote scale adherence in other similar alloy systems.

Table 75 is a compilation of the alloy systems which were initially made and fabricated to 15 mil sheet for evaluation. Five of the heats were made as 45.4 kg.(100 lb.) units. Both nominal and analyzed compositions were reported. Special analyses were made for the aluminum containing alloys and both metallic aluminum and total aluminum contents have been reported. All of the alloys prepared under Section III-3 were also evaluated for oxidation behavior.

The scouting test procedure selected was limited to delineating the superiority of one materials system over another since the construction of a test rig simulating the anticipated space shuttle environment was beyond the scope of the program. However, the observations made, were found to conform in a semi-quantitative manner with those made at other NASA test facilities.

A dynamic oxidation test rig was assembled at Fansteel Baltimore for scouting tests on the series of alloys being investigated. A schematic of the test rig is shown in Figure 74. The test specimens consisted of flat coupons, 1.59 x 2.54 x 0.038 cm.(5/8 x 1 x 0.015 in.) fitted into slots in metallic specimen holders. Initially four and later eight such specimens were placed in holders in 5.08 cm.(2 in.) diameter tubes in a furnace at 1204°C(2200°F) and exposed to a 9-15 m/sec.(30-50 ft./sec.) stream of combustion products from gas burners located at one end of the tubes. Each test, of a nominal 40-50 hour duration with cooling cycles every half hour to below 538°C(1000°F), utilized one or two standard TDNiCr specimens (Heat 3304) and three or six test alloy specimens. Weight change data were recorded, initially at 1 hour intervals and later at approximately 8 hour intervals. Each four hours specimens were rotated from position to position to eliminate the effect of sample location on results. After testing, the specimens were subjected to metallographic examination. In addition, the surfaces were analyzed by X-ray diffraction and electron microprobe analysis where warranted.

TABLE 75

OXIDATION IMPROVEMENT TDNiCr BASE ALLOYS

HEAT NO.	NOMINAL COMPOSITION	ANALYZED COMPOSITION(1)
3335	Ni-16Cr-2ThO_2	Ni-18Cr-2.2ThO_2
3336	Ni-16Cr-3.5Al-2ThO_2	Ni-16Cr-3.2(3.5)Al-2.3ThO_2
3337	Ni-16Cr-4.5Al-2ThO_2	Ni-16Cr-4.2(4.5)Al-2.3ThO_2
3338	Ni-16Cr-5.5Al-2ThO_2	Ni-16Cr-5.1(5.5)Al-2.3ThO_2
3339	Ni-20Cr-4.5Al-2ThO_2	Ni-19Cr-4.1(4.4)Al-2.2ThO_2
3340	Ni-20Cr-5.5Al-2ThO_2	Ni-19Cr-5.2(5.6)Al-2.2ThO_2
3348	Ni-20Cr-15Fe-2ThO_2	Ni-19Cr-15Fe-2.2ThO_2
3350	Ni-30Cr-15Fe-2Mn -0.5Si-0.3La-2ThO_2	Ni-30Cr-14Fe-1.7Mn -0.6 Si-0.4La-2.3ThO_2
3351	Ni-16Cr-5.5Al-0.3La-2ThO_2	Ni-15Cr-5.4(6.2)Al-0.4La-2.2ThO_2
3352	Ni-16Cr-5.5Al-0.4Y-2ThO_2	Ni-16Cr-5.9(6.2)Al-2.3ThO_2
3379	Ni-16Cr-5.5Al-0.5Th-2ThO_2	Ni-16Cr-5.2(5.6)Al-0.6-2.3ThO_2
3380	Ni-20Cr-5.5Al-0.3La-2ThO_2	Ni-19Cr-3.2(4.4)Al-0.3La-2.2ThO_2
3381	Ni-20Cr-3.5Al-2ThO_2	Ni-20Cr-3.3(3.6)Al-2.2ThO_2
3388	Ni-30Cr-3.5Al-2ThO_2	Ni-30Cr-3.1(3.4)Al-2.2ThO_2
3389	Ni-20Cr-5.5Al-0.2Y-2ThO_2	Ni-18Cr-5.2(5.5)Al-0.2Y -2.2ThO_2
3390	Ni-23Cr-14Fe-1.5Al -0.2Si-2ThO_2	Ni-24Cr-14Fe-1.4Al -0.1Si-2.2ThO_2
3391	Ni-16Cr-15Fe-2ThO_2	Ni-18Cr-16Fe-2.2ThO_2
3392	Ni-20Cr-15Fe-2Mn -0.5Si-0.3La-2ThO_2	Ni-21Cr-15Fe-2Mn -0.6Si-0.3La-2.2ThO_2
3399	Ni-16Cr-15Fe-2Mn-0.5Si -0.3La-2ThO_2	Ni-16Cr-15Fe-1.8Mn- -1.1Si-0.3La-2.3ThO_2
3409	Ni-20Cr-25Fe-2ThO_2	Ni-20Cr-25Fe-2.3ThO_2
3410	Ni-20Cr-4Mn-2ThO_2	Ni-20Cr-4Mn-2.3ThO_2
3412	Ni-20Cr-15Fe-2ThO_2	Ni-22Cr-16Fe-2.3ThO_2
3413	Ni-20Cr-15Fe-2Mn-2ThO_2	Ni-21Cr-15Fe-2Mn-2.5ThO_2
3429	Ni-16Cr-5.5Al-0.2Y-2ThO_2	Ni-15Cr-5.3(5.8)Al-0.2Y -2.3ThO_2

(1) Figures in parentheses refer to total Al content

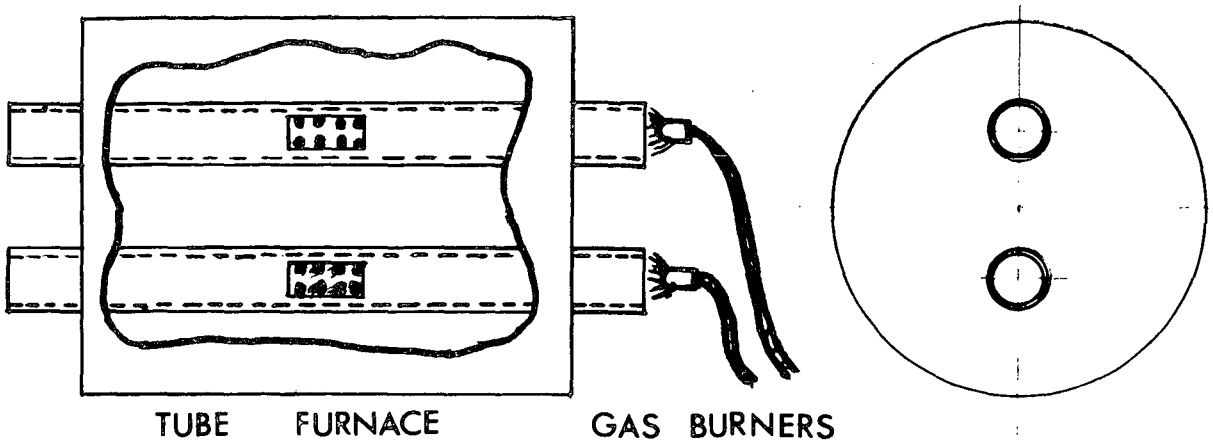
TABLE 75
(Cont'd)

OXIDATION IMPROVEMENT TDNiCr BASE ALLOYS

HEAT NO.	NOMINAL COMPOSITION	ANALYZED COMPOSITION(1)
**3504	Ni-16Cr-15Fe-2Mn-0.5Si-0.3La-2ThO_2	Ni-15Cr-1.6Mn-0.6Si-0.3La 2.4ThO_2
**3505	Ni-16Cr-3.5Al-0.2Y-2ThO_2	Ni-16Cr-2.6(3.5)Al-0.2Y-2.2ThO_2
3542	Ni-16Cr-4.5Al-2ThO_2	Ni-16Cr-3.9(4.5)Al-2.2ThO_2
3543	Ni-9Cr-3Al-2ThO_2	Ni-8.6Cr-2.5(2.9)Al-2.2ThO_2
**3563	Ni-16Cr-3.5Al-2ThO	Ni-14Cr-2.7(3.1)Al-2.3ThO_2
**3564	Ni-20Cr-3.5Al-0.2Y-2ThO_2	Ni-19Cr-2.8(3.1)Al-0.2Y-2.2ThO_2
**3575	Ni-20Cr-3.5Al-2ThO_2	Ni-19Cr-2.8(3.3)Al-2.2ThO_2
3577	Ni-4Cr-4Al-2ThO_2	Ni-3.5Cr-3.1(3.5)Al-2.5ThO_2
3579	Ni-4Cr-6Al-2ThO_2	Ni-3.6Cr-5.1(5.4)Al-2.5ThO_2
3580	Ni-9Cr-4Al-2ThO_2	Ni-8.2Cr-3.4(3.8)Al-2.4ThO_2
3581	Ni-9Cr-5Al-2ThO_2	Ni-8.7Cr-4.1(4.8)Al-2.4ThO_2
3582	Ni-9Cr-6Al-2ThO_2	Ni-8.5Cr-5.5(5.8)Al-2.4ThO_2

(1) Figures in parentheses refer to total Al content

** 45.4 kg (100 lb.) units



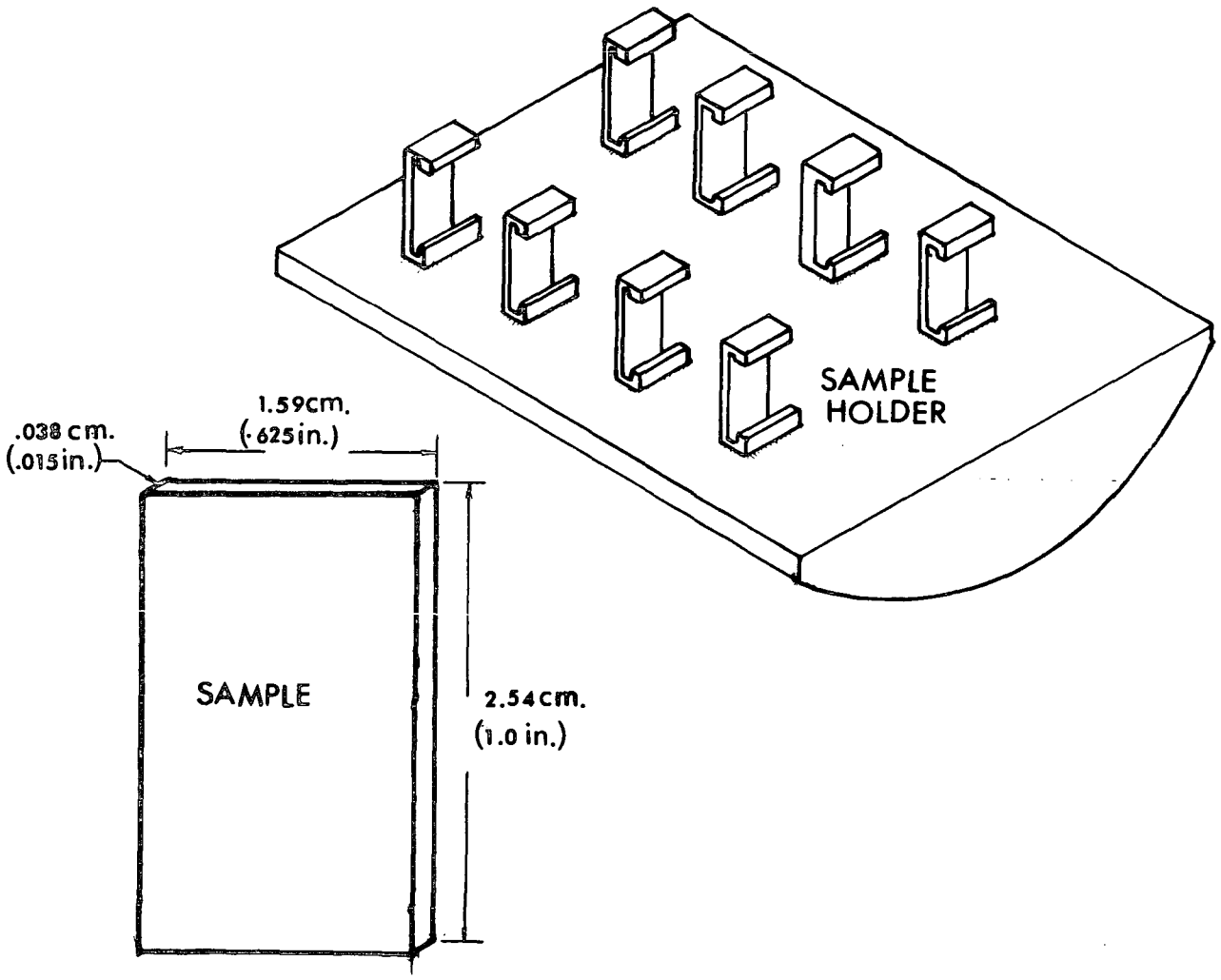


FIGURE 74

OXIDATION TEST RIG

c. Oxidation of Modified TDNiCr Alloys

The least complex of the alloys studied were those fabricated under Section III-3. In all cases during the early stages of testing, a thin, adherent, grey-black layer of Cr_2O_3 was formed on both front and back faces of the test specimens. At equilibrium, which was generally attained within one or two hours, the diffusion of Cr through the non-thickening Cr_2O_3 scale balanced the loss of Cr via the formation of CrO_3 gas. At this point test specimens lost weight in a more or less linear manner. Some specimens exhibited this behavior throughout the duration of the test. On the other hand some of the specimens, including the standard TDNiCr Heat 3304, showed a breakdown of the Cr_2O_3, first at edges. With the progression of test time, the breakdown could be observed to move inward towards the center of the front faces. X-ray diffraction of areas showing accelerated attack revealed that NiO and $NiCr_2O_4$ had replaced the Cr_2O_3 inasmuch as Cr depletion via CrO_3 formation had been sufficiently high to preclude the possibility of maintaining the Cr_2O_3 scale. Whenever Cr_2O_3 breakdown occurred, surface metal was lost; where Cr_2O_3 was retained, essentially no surface metal was lost. In the latter case, however, internal porosity resulted. The chief reason for differences in the incubation period was that of variations in the grain size among the heats tested. Fine grain sheet stock, in general, had a longer incubation period since the Cr could diffuse faster through the sheet via grain boundaries and thereby maintain equilibrium.

In order to describe the alloys a classification system has been developed. The type of oxidation behavior observed for the standard TDNiCr and TDNiCr with minor additions has been classified as Type B. A following digit 1, 2, or 3 refers to; 1, little or no Cr_2O_3 breakdown (at edges); 2, attack limited to the vicinity of specimen edges; or 3, attack spread well beyond specimen edges. A second following digit 1, 2 or 3 describes the extent of intergranular oxidation as; 1, little; 2, moderate; or 3, excessive.

Table 76 is a compilation of the results obtained with the alloys of Section III-3. Weight change data curves for the alloy systems tested can be found in APPENDIX F. The curves reflect net weight changes due to losses of material through CrO_3 volatilization and spalling of NiO and $NiCr_2O_4$, and weight increases due to oxygen pickup. Figures 75, 76 and 77 are photomicrographs of selected areas of typical specimens which exhibited type B behavior.

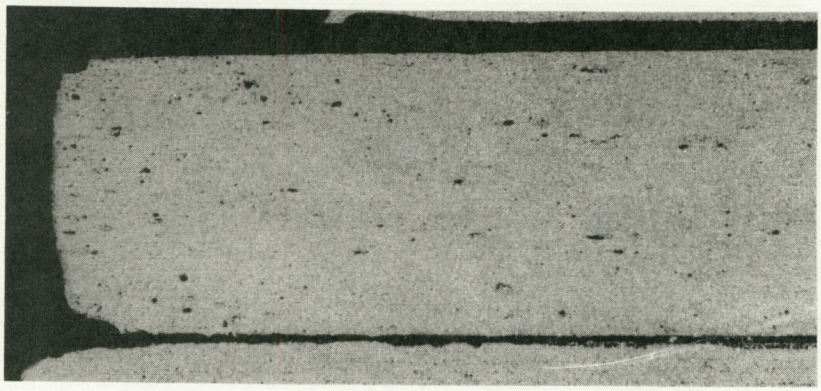
d. Oxidation of TDNiCr Base Alloys

The Fe, Mn, Si, La modified alloys were designated as Type AB systems. Here a following digit 1, 2 or 3 referred to slow, moderate or rapid oxidation kinetics, respectively. A second following digit 1, 2 or 3 referred to the extent of internal or intergranular oxidation, little, moderate or extensive, respectively.

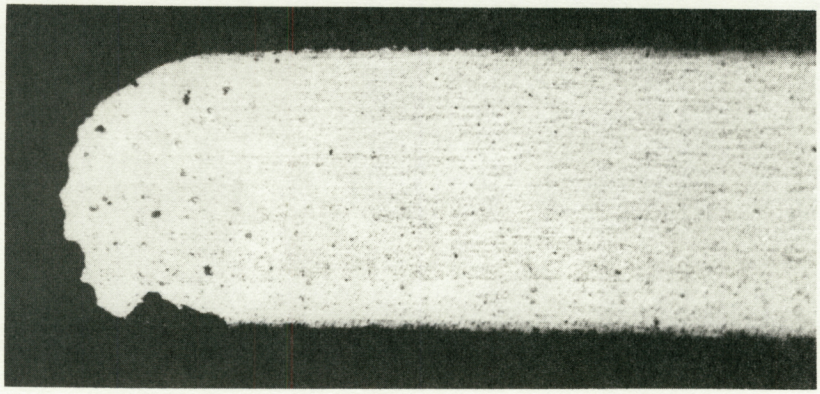
TABLE 76

OXIDATION CLASSIFICATION OF MODIFIED TDNiCr ALLOYS

Heat No.	Nominal Composition	Classification
3304	Standard TC	B-3-1
3333	Ni-20Cr-0.5ThO_2	B-1-1
3334	Ni-20Cr-1.0ThO_2	B-3-1
3343	Ni-20Cr-2ThO_2	B-2-1
3364	Ni-20Cr-2ThO_2(0.05LiH)	B-3-1
3365	Ni-20Cr-2ThO_2(0.01LiH)	B-3-1
3366	Ni-20Cr-2ThO_2(0.1LiH)	B-3-1
3367	Ni-20Cr-2ThO_2(0.05CaH_2)	B-3-1
3368	Ni-20Cr-2ThO_2(0.1CaH_2)	B-2-1
3369	Ni-20Cr-2ThO_2(0.1NH_4Cl)	B-3-1
3370	Ni-20Cr-2ThO_2(0.1NH_4F)	B-2-1
3411	Ni-20Cr-1.5ThO_2	B-3-1
3420	Ni-20Cr-0.3Zr-2ThO_2	B-2-1
3427	Ni-20Cr-0.3Ti-2ThO_2	B-1-1
3428	Ni-20Cr-0.2Si-2ThO_2	B-1-1
3432	Ni-20Cr-0.1Si-2ThO_2	B-2-1
3433	Ni-20Cr-0.3Mg-2ThO_2	B-2-1
3448	Ni-20Cr-0.1Al-2ThO_2	B-3-1
3449	Ni-20Cr-0.2Al-2ThO_2	B-3-1
3450	Ni-20Cr-0.6Y-2ThO_2	B-3-1
3459	Ni-20Cr-0.7Th-2ThO_2	B-2-1
3460	Ni-20Cr-1.4Th-2ThO_2	B-3-1
3461	Ni-20Cr-1.2La-2ThO_2	B-3-1
3462	Ni-20Cr-0.3Y-2ThO_2	B-3-1



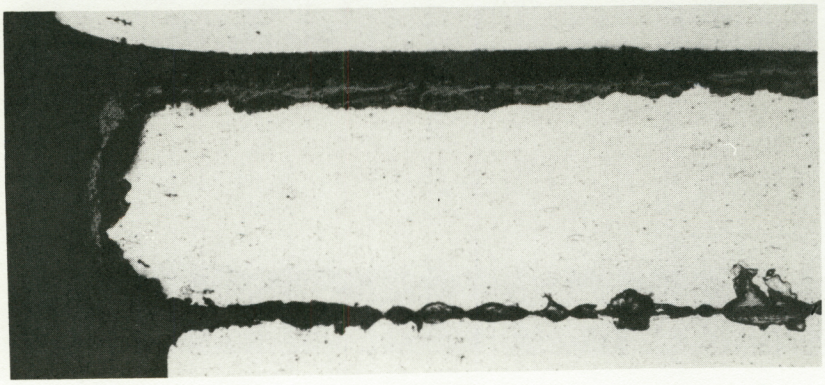
Heat 3431 - Exposed Edge of Sheet
($Ni-20Cr-0.15Ti-2ThO_2$)



Heat 3333 - Exposed Edge of Sheet
($Ni-20Cr-0.5ThO_2$)

FIGURE 75

Photomicrographs of Oxidation Test Specimens. Typical Type B-1-1 Behavior X100



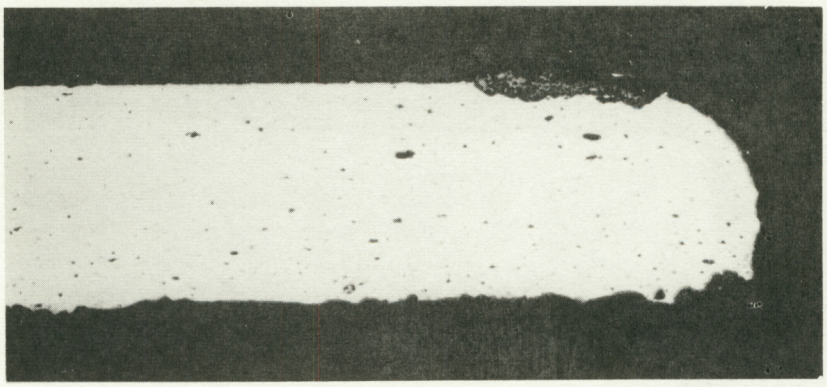
Heat 3420 - Exposed Edge of Sheet
($Ni-20Cr-0.3Zr-2ThO_2$)



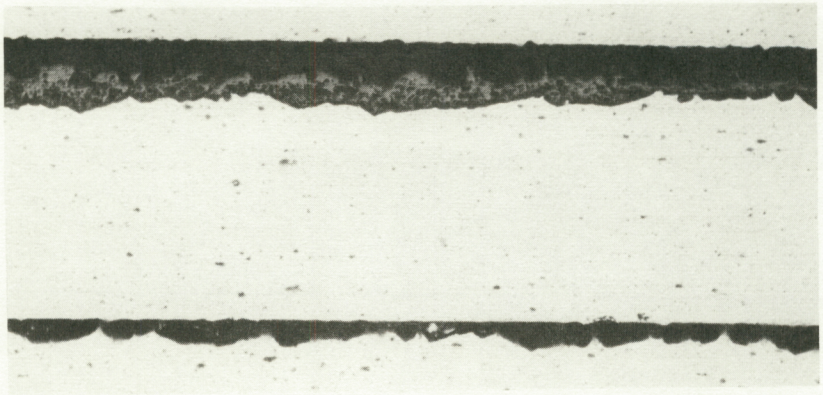
Heat 3420 - Center of Sheet

FIGURE 76

Photomicrographs of Oxidation Test Specimens. Typical Type B-2-1 Behavior X100



Heat 3304 - Exposed Edge of Sheet
(Standard TDNiCr, Ni-20Cr-2ThO_2)



Heat 3304 - Center of Sheet

FIGURE 77

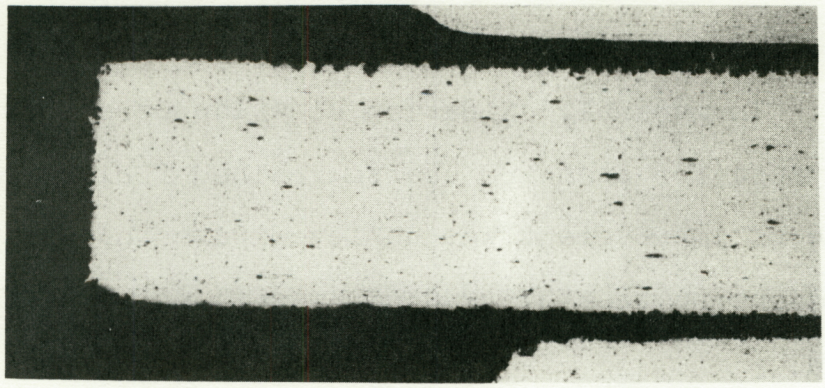
Photomicrographs of Oxidation Test
Specimens. Typical Type B-3-1 Behavior X100

Those alloys free of Mn formed essentially pure Cr_2O_3 on the rear faces of the test specimens; however, on the front faces Cr_2O_3 was found overgrown by spinels of Fe, Ni and Cr oxide. In general, oxidation kinetics were somewhat lower than those for standard coarse grained TDNiCr. A greater degree of improvement was achieved with the addition of Mn. Subsequent to testing, $MnCr_2O_4$ was found to be the major oxide formed.

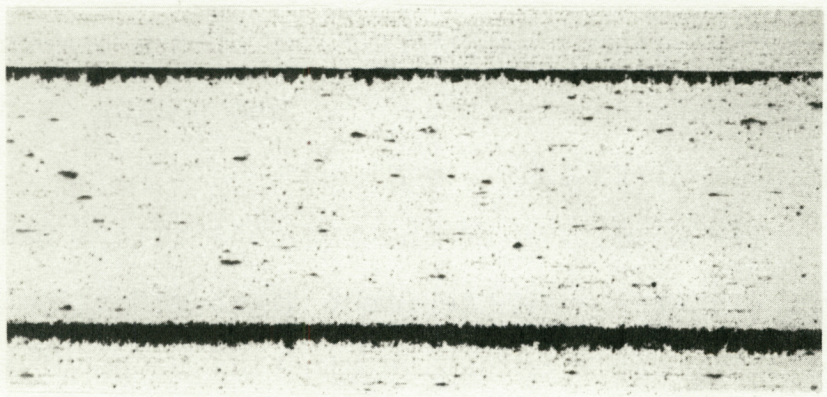
The lowest rates of oxidation were achieved with those alloys containing Fe, Mn, Si and La in combination, although internal porosity developed and was fairly severe. Photomicrographs of typical type AB behavior are shown in Figures 78 and 79.

The classifications of the alloys showing type AB behavior are given in Table 77. The weight change data are included in APPENDIX F.

The oxidation of the TDNiCrAl alloys was designated as Type A system with the first digit referring to slow, moderate, or rapid oxidation kinetics respectively and the second digit referring to the extent of internal or intergranular oxidation as little, moderate or extensive respectively. The classification of the alloys tested are given in Table 77 and the weight change data are included in APPENDIX F. Photomicrographs of specimens exhibiting typical type A behavior are shown in Figures 80, 81 and 82.



Heat 3392 - Exposed Edge of Sheet



Heat 3392 - Center of Sheet

FIGURE 78

Photomicrographs of Oxidation Test Specimens. Typical Type AB-1-1 Behavior X100



Heat 3391 - Exposed Edge of Sheet
(Ni-16Cr-15Fe-2ThO_2)



Heat 3391 - Center of Sheet

FIGURE 79

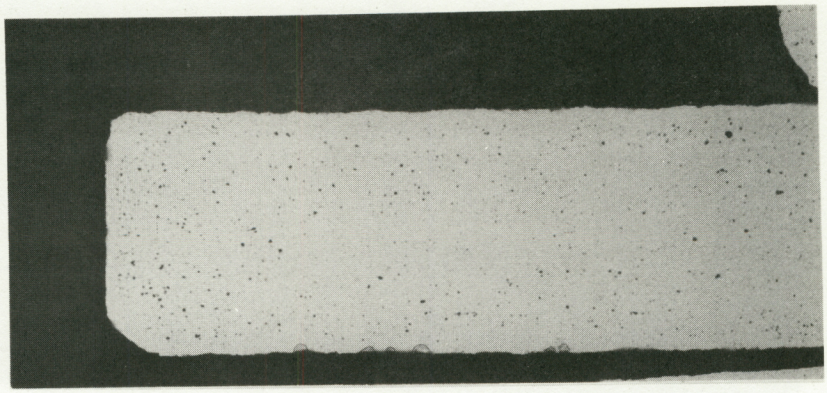
Photomicrographs of Oxidation Test Specimens. Typical Type AB-2-1 Behavior X100

TABLE 77

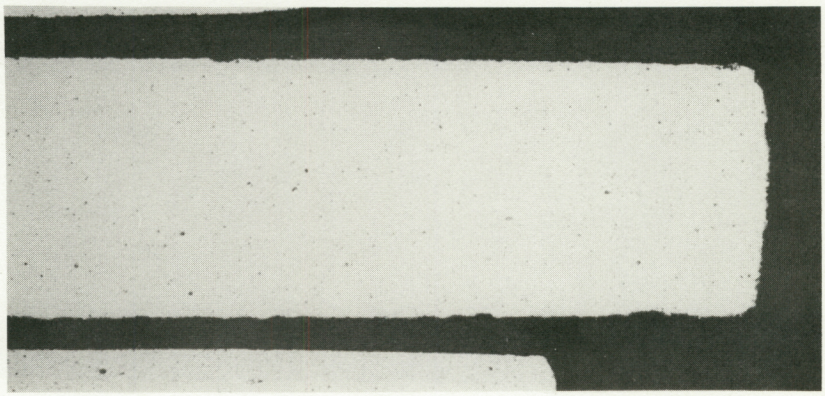
OXIDATION CLASSIFICATION OF TDNiCr BASE ALLOYS

Heat No.	Nominal Composition	Classification
3335	Ni-16Cr-2ThO_2	B-3-1
3409	Ni-20Cr-25Fe-2ThO_2	AB-2-1
3410	Ni-20Cr-4Mn-2ThO_2	AB-1-1
3412	Ni-20Cr-15Fe-2ThO_2	AB-2-1
3413	Ni-20Cr-15Fe-2Mn-2ThO_2	AB-2-1
3391	Ni-16Cr-15Fe-2ThO_2	AB-2-1
3392	Ni-20Cr-15Fe-0.5Si-0.3La-2Mn-2ThO_2	AB-1-1
3399	Ni-16Cr-15Fe-2Mn-0.5Si-0.3La-2ThO_2	AB-1-1
3390	Ni-23Cr-14Fe-1.5Al-0.2Si-2ThO_2	AB-2-3
*3504	Ni-16Cr-15Fe-2Mn-0.5Si-0.3La-2ThO_2	AB-1-1
3336	Ni-16Cr-3.5Al-2ThO_2	A-1-1
3337	Ni-16Cr-4.5Al-2ThO_2	A-1-1
3338	Ni-16Cr-5.5Al-2ThO_2	A-1-1
3339	Ni-20Cr-4.5Al-2ThO_2	A-1-1
3340	Ni-20Cr-5.5Al-2ThO_2	A-1-1
3429	Ni-16Cr-5.5Al-0.2Y-2ThO_2	A-1-1
3351	Ni-16Cr-5.5Al-0.3La-2ThO_2	A-1-2
3352	Ni-16Cr-5.5Al-0.4Y-2ThO_2	A-1-1
3379	Ni-16Cr-5.5Al-0.5Th-2ThO_2	A-1-1
3380	Ni-20Cr-5.5Al-0.3La-2ThO_2	A-1-2
3381	Ni-20Cr-3.5Al-2ThO_2	A-1-1
3388	Ni-30Cr-3.5Al-2ThO_2	A-1-1
3389	Ni-20Cr-5.5Al-0.2Y-2ThO_2	A-1-1
3542	Ni-16Cr-4.5Al-0.2Y-2ThO_2	A-1-1
3543	Ni-9Cr-3Al-2ThO_2	A-1-2
*3505	Ni-16Cr-3.5Al-0.2Y-2ThO_2	A-1-3
*3563	Ni-16Cr-3.5Al-2ThO_2	A-1-2
*3564	Ni-20Cr-3.5Al-0.2Y-2ThO_2	A-1-2
*3575	Ni-20Cr-3.5Al-2ThO_2	A-1-3
3577	Ni-4Cr-4Al-2ThO_2	A-3-3
3579	Ni-4Cr-6Al-2ThO_2	A-1-2
3580	Ni-9Cr-4Al-2ThO_2	A-3-3
3581	Ni-9Cr-5Al-2ThO_2	A-1-2
3582	Ni-9Cr-6Al-2ThO_2	A-1-2

* 45.4 kg (100 lb.) unit



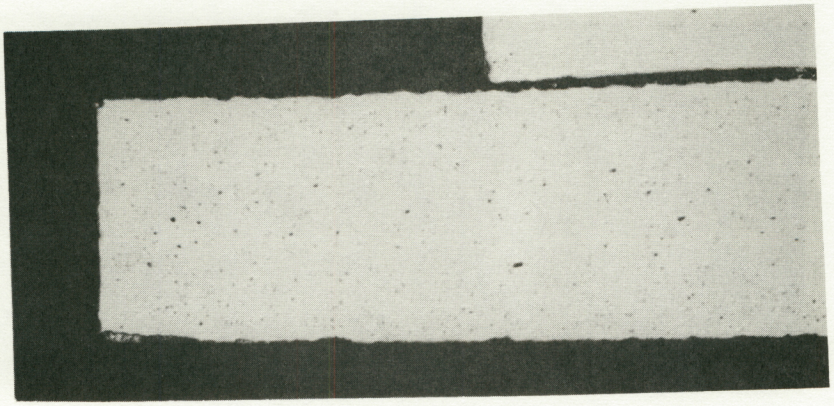
Heat 3389 - Exposed Edge of Sheet
($Ni-20Cr-5.5Al-0.2Y-2ThO_2$)



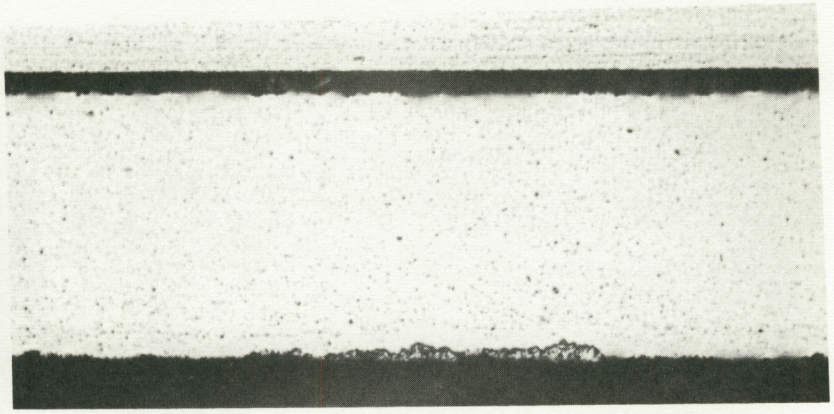
Heat 3336 - Exposed Edge of Sheet
($Ni-16Cr-3.5Al-2ThO_2$)

FIGURE 80

Photomicrographs of Oxidation Test Specimens. Typical Type A-1-1 Behavior X100



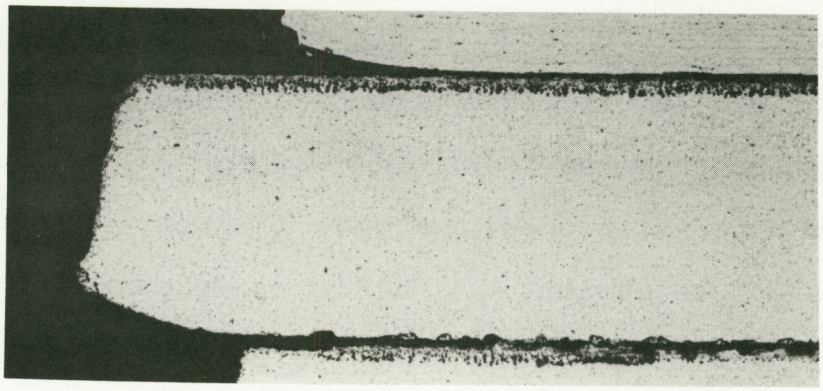
Heat 3380 - Exposed Edge of Sheet
($Ni-20Cr-5.5Al-0.3La-2ThO_2$)



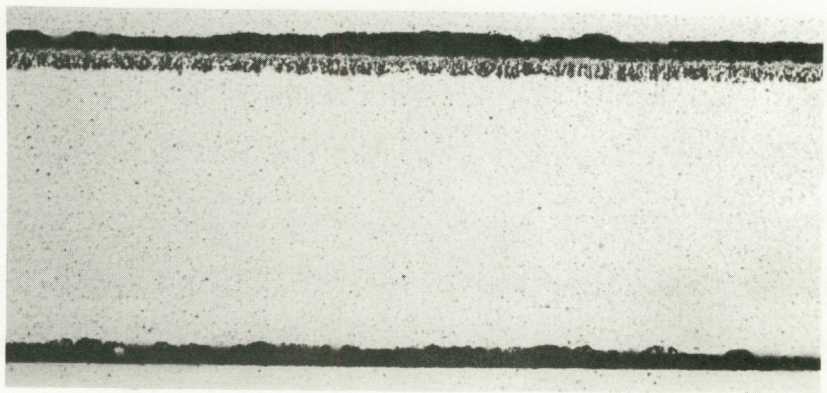
Heat 3380 - Center of Sheet

FIGURE 81

Photomicrographs of Oxidation Test
Specimens. Typical Type A-1-2 Behavior X100



Heat 3505 - Exposed Edge of Sheet
($Ni-16Cr-3.5Al-0.2Y-2ThO_2$)



Heat 3505 - Center of Sheet

FIGURE 82

Photomicrographs of Oxidation Test Specimens. Typical Type A-1-3 Behavior X100

One 50 hour run was made at 1260°C(2300°F) with the best specimens having a type A or AB classification. The weight change data are shown in Figure 83. The type A specimens showed little or no degradation and are considered potentially useful to at least 1260°C(2300°F).

The type A-1-1 specimens were the most oxidation resistant of those evaluated. In the early stages of testing a thin grey layer of Al_2O_3 formed. With increasing test time $NiAl_2O_4$ appeared with its characteristic blue color. These observations were confirmed by X-ray diffraction. Rare earth additions appeared to have no influence at all on performance.

Instances of anomalous behavior of the Ni-Cr-Al-ThO_2 alloys were observed with Heats 3351, 3380 and the first four 45.4 kg. (100 lb.) units comprising Heats 3505, 3563, 3564 and 3575. With these heats, in the early stages of testing irregular patches of Cr_2O_3 were formed on surfaces. With increasing test time the blotches would either persist, or spall off and be replaced by NiO(green), or spall off and be replaced by a continuous Al_2O_3 film(grey) or spall off and be replaced with $NiAl_2O_4$(blue). Where the Cr_2O_3 persisted metallographic examinations showed internal oxidation which proved to be Al_2O_3 by both XRD and electron microprobe analysis. The depth of this internal oxidation varied considerably from heat to heat. In fact, with the low Cr series (Heats 3576-3582), where Cr_2O_3 formation was the rule rather than the exception, one of these specimens

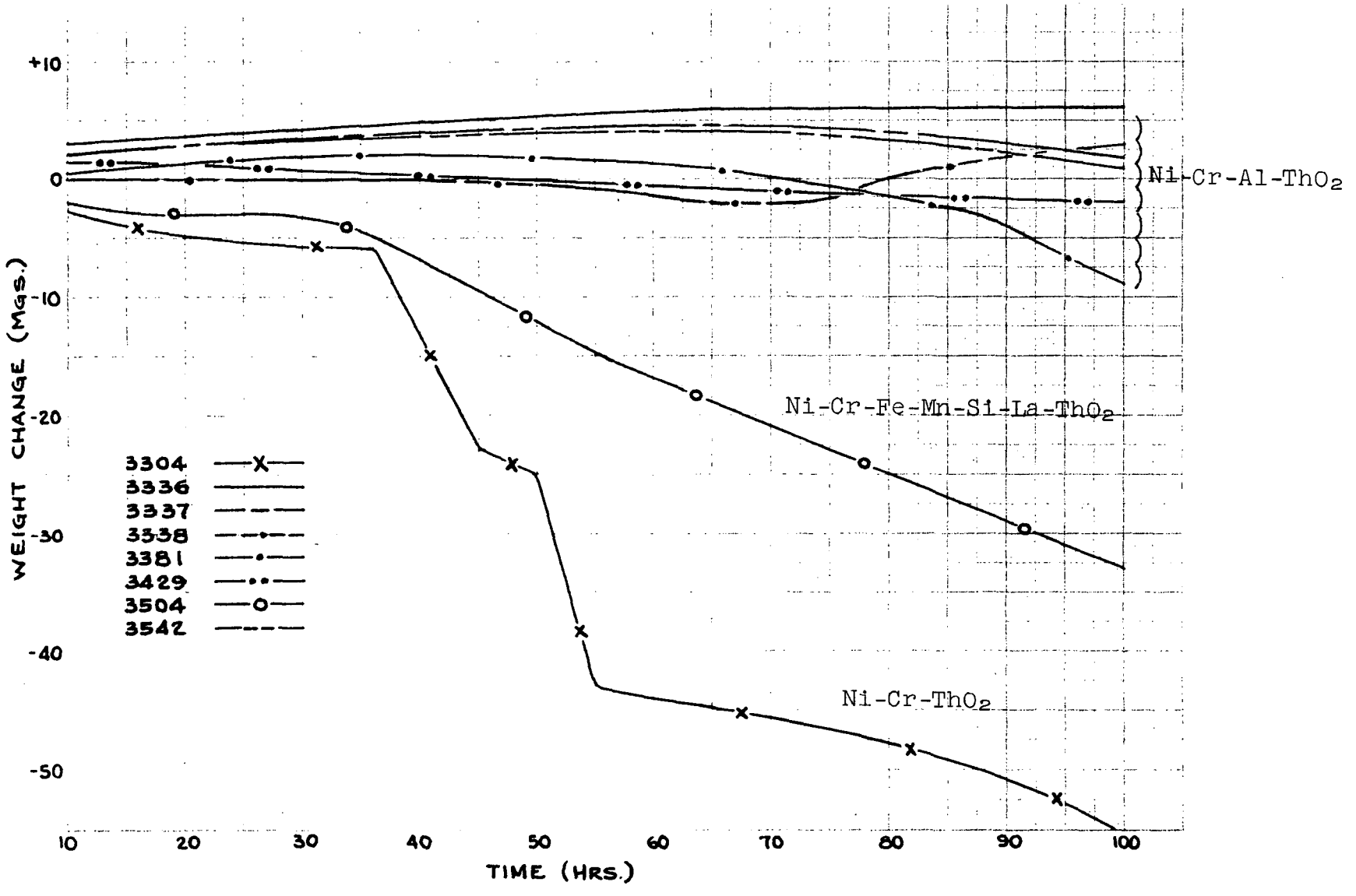


FIGURE 83 WEIGHT CHANGE VS TIME - 1260°C(2300°F) CYCLIC OXIDATION TEST

literally disintegrated. To gain further insight into this seemingly erratic behavior close examination of as-received material revealed Al depletion in certain areas owing to insufficient surface grinding. These areas would form Cr_2O_3 when exposed to static air at 1204°C(2200°F). Experiments performed at 1121°C(2050°F) in static air showed that all heats fabricated, regardless of Al content, formed both Cr_2O_3 and Al_2O_3 at this lower temperature. Thus, although proper sheet conditioning could avoid the likelihood of Cr_2O_3 formation at 1204°C(2200°F), there still appeared to be a possible problem at lower temperatures.

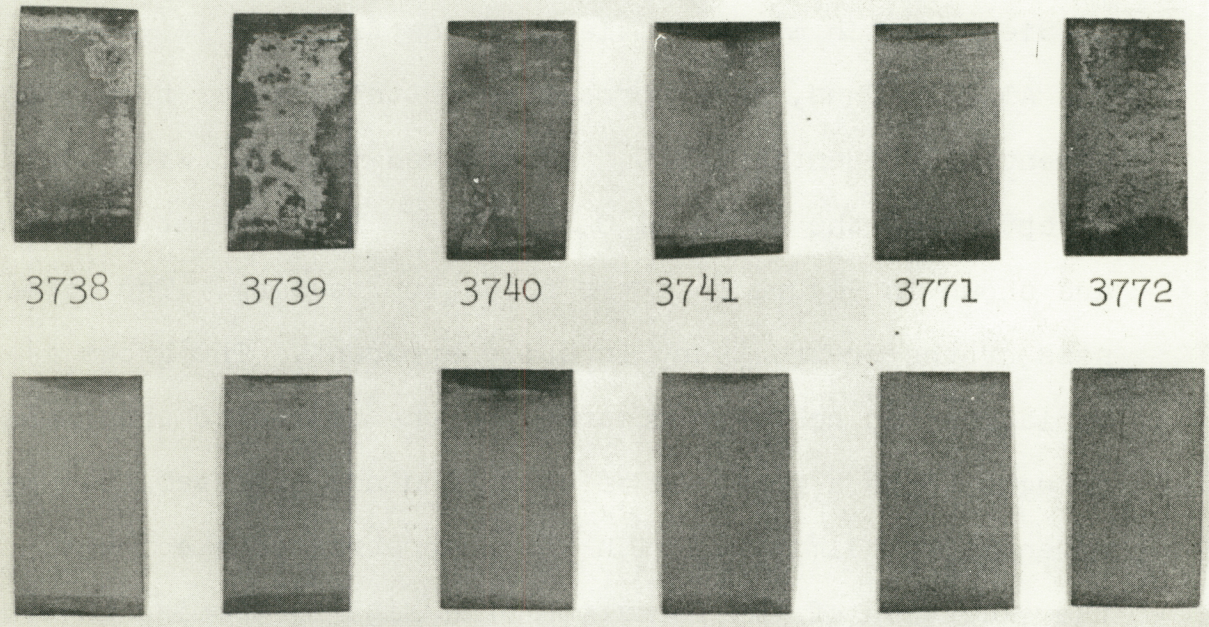
A key observation made during this study was that once an Al_2O_3 scale was established it would persist; $NiAl_2O_4$ would tend to form with the passage of time, but no Cr_2O_3 would form. Therefore, any means whereby Al_2O_3 exclusively could be formed on a sheet's surface prior to use might prove beneficial.

During the oxidation tests on 0.038 cm. (0.015 in.) sheet from a series of 45.4 kg. (100 lb.) scale-up alloy units the anomalous behavior was again observed. Specimens from each of six different alloy heats were being rig tested at 1204°C(2200°F). All specimens developed a Cr_2O_3 scale in the early stages of testing. During the course of the test each specimen developed varying amounts of Al_2O_3, $NiAl_2O_4$, Cr_2O_3 and NiO and performance was less than expected. A second group of specimens from the same heats were then heat-treated in H_2 for six hours at 1177°C(2150°F) to develop an

Al_2O_3 layer. The temperature was sufficiently high to prevent the formation of Cr_2O_3 at the low dew point of the hydrogen atmosphere (input hydrogen, -68°C[-90°F]). Although an Al_2O_3 film can be formed in a relatively short time, an extended cycle was utilized in an effort to remove any concentration gradients which might initially arise from the formation of the Al_2O_3. Thus, sheet processed in this manner should be essentially identical with as-received material with the exception of the added Al_2O_3 coating. The two sets of samples are shown in Figure 84 after oxidation testing. The effectiveness of the pretreatment is quite apparent. The gross variations in behavior observed on the untreated specimens are thought to be a function of conditioning; this variable was essentially eliminated with the H_2 pretreated specimens. With the exception of the formation of a $NiAl_2O_4$ tarnish in stagnant areas where the specimens were held at their ends in the slotted fixtures and on the rear faces, the treated group was almost literally unaffected by the oxidation test. All these specimens gained weight during the test, the largest net increase being only 0.5 mg/cm^2.

The effectiveness of the preheat treatment in hydrogen was further demonstrated on a low chromium level alloy; a specimen from Heat 3543 (Ni-9Cr-3Al-2ThO_2) was H_2 heat-treated and oxidation tested. It performed as well as the other H_2 heat-treated specimens.

SPECIMENS NOT PREOXIDIZED



SPECIMENS SELECTIVELY
PREOXIDIZED FOR 6 HRS. @ 1177°C(2150°F) IN H_2

3738-Ni-16Cr-3.5Al-2ThO_2
3739-Ni-16Cr-4.0Al-2ThO_2
3740-Ni-16Cr-4.5Al-2ThO_2
3741-Ni-16Cr-4.0Al-1.5ThO_2
3771-Ni-16Cr-4.0Al-0.2Y-2ThO_2
3772-Ni-16Cr-3.5Al-0.2Y-2ThO_2

FIGURE 84

PHOTOGRAPH OF TDNiCrAl ALLOYS AFTER CYCLIC OXIDATION TEST
45 Hours at 1204°C(2200°F)

e. Modified TDNiCrAl Alloys

Small scale units of TDNiCrAl were made with minor alloy additions of Mn, CaH_2 and NH_4Cl to try to determine their effect on the anomalous oxidation behavior and on the excess oxygen level in this alloy.

In an attempt to beneficially alter the relative diffusion rates of Cr and Al, three 4.54 kg. (10 lb.) units containing small amounts of Mn were evaluated. At the same time, 4.54 kg. (10 lb.) units containing NH_4Cl and CaH_2 additions were processed to sheet and evaluated. These units represented an attempt at decreasing the excess oxygen in the sheet. Table 78 is a listing of this series of alloys. As can be seen the halide and hydride additions had little effect on producing a low oxygen material.

Specimens from these heats were all rig tested at 1204°C (2200°F). No benefit was derived from the heats containing Mn. In fact, its presence appeared to suppress the formation of Al_2O_3. The CaH_2 and NH_4Cl group of alloys developed gross internal oxidation and were among the worst performers evaluated in this program.

f. Mechanical Properties TDNiCr Base Alloys

Only survey testing was done on the small scale alloys. Various mechanical properties of the 0.038 cm. (0.015 in.) sheet fabricated from the alloys are compiled in Table 79. Since processing history can profoundly affect final properties and these alloys are new, the results are only an indication of potential strength, ductility, and formability. In addition

TABLE 78

MODIFIED TDNiCrAl ALLOYS

Heat No.	Nominal Composition	Excess Oxygen (ppm)
3749*	Ni-16Cr-4Al-2ThO_2	2570
3750	Ni-16Cr-4Al-0.2Mn-2ThO_2	1870
3751	Ni-16Cr-4Al-0.5Mn-2ThO_2	**
3752	Ni-16Cr-4Al-1.0Mn-2ThO_2	1000
3755	Ni-16Cr-4Al-0.05CaH_2-2ThO_2	4160
3756	Ni-16Cr-4Al-0.1CaH_2-2ThO_2	2150
3757	Ni-16Cr-4Al-0.5NH_4Cl-2ThO_2	2210
3758	Ni-16Cr-4Al-0.1NH_4Cl-2ThO_2	1360

* Baseline

** Not reported

the contaminant levels, especially of carbon and oxygen were not under complete control from heat to heat and could very well have influenced the results reported. These areas are to be intensively evaluated in Part II of the program.

The results obtained thus far indicate that relatively high strength in combination with ductility can be realized with modified TDNiCr alloys.

Of special interest is that the Al modified alloys which demonstrated superior oxidation resistance show a high strength capability as well as reasonable ductility in this initial investigation.

g. γ' Phase

The initial TDNiCrAl alloy studies indicated that the γ' phase would be encountered with some of the compositions being investigated. The γ' Phase might be expected to cause a loss in ambient ductility.

The γ' precipitation can be detected through X-ray diffraction by scanning across the (100) and (110)d spacings for Ni_3Al; the balance of the lines are obscured by matrix peaks. It has been found that γ' will precipitate on very slow cooling (furnace cooled) in Ni-16 to 20 Cr base alloys with as little as 3.2 percent Al in solution. It was not detected in a heat containing 2.8 percent free Al which had been similarly heat-treated.

At the program's inception it had been postulated that a minimum of about 3.0 to 3.5 percent Al was required to suppress Cr_2O_3 formation. With the use of the H_2 heat-treatment

TABLE 79

MECHANICAL PROPERTIES OF TDNiCr BASE ALLOYS

Heat No.	Nominal Composition	Room Temperature UTS MN/m^2	Room Temperature YS MN/m^2	Room Temperature Elong. %	1093°C UTS MN/m^2	1093°C YS MN/m^2	1093°C Elong. %	1093°C 4500 psi S/R Hrs.	Trans. Bend Radius 105°
3335	Ni-16Cr-2ThO_2	862.5	730.2	26.0	100.0	100.0	8.0	>20	2T
3341	Ni-30Cr-2ThO_2	789.5	724.6	14.0	57.9	50.3	10.0	Failed on loading	4T
3336	Ni-16Cr-3.5Al-2ThO_2	1121.1	843.9	11.5	89.6	80.0	5.5	>20	3T
3337	Ni-16Cr-4.5Al-2ThO_2	1086.6	833.6	9.5	91.7	75.8	5.0	>20	3.5T
3338	Ni-16Cr-5.5Al-2ThO_2	1063.9	979.8	10.1	84.1	82.0	7.5	>20	12T
3339	Ni-20Cr-4.5Al-2ThO_2	1172.1	899.8	9.5	92.4	88.9	4.0	>20	5T
3340	Ni-20Cr-5.5Al-2ThO_2	1185.9	1002.5	7.5	99.3	78.6	6.0	6.2	>8T
3429	Ni-16Cr-5.5Al-0.2Y-2ThO_2	1134.9	947.3	16.0	84.8	76.5	5.5	>20	7T
3351	Ni-16Cr-5.5Al-0.3La-2ThO_2	1047.3	1047.3	10.0	91.7	84.8	10.0	20	>11T
3352	Ni-16-Cr-5.5Al-0.4Y-2ThO_2	1027.3	768.8	10.0	96.2	71.7	10.0	>20	8T
3379	Ni-16Cr-5.5Al-0.5Th-2ThO_2	1031.5	1031.5	13.0	82.7	78.6	11.0	>20	8T
3380	Ni-20Cr-5.5Al-0.3La-2ThO_2	1207.3	1032.2	13.0	90.3	82.7	20.0	>20	8T
3381	Ni-20Cr-3.5Al-2ThO_2	1067.3	810.1	8.5	101.4	91.7	4.0	>20	>6T
3388	Ni-30Cr-3.5Al-2ThO_2	1174.9	1168.0	13.0	93.8	77.9	11.0	0.9	8T
3389	Ni-20Cr-5.5Al-0.2Y-2ThO_2	1199.0	980.4	10.0	87.6	82.0	11.0	0.1	10T
3577	Ni-4Cr-4Al-2ThO_2	715.0	612.9	15.0	96.5	77.9	15.0	>20	>9T
3579	Ni-4Cr-6Al-2ThO_2	825.3	673.6	16.0	96.5	85.5	11.2	>20	4T
3580	Ni-9Cr-4Al-2ThO_2	641.2	464.0	24.0	96.5	90.3	15.0	>20	7T
3582	Ni-9Cr-6Al-2ThO_2	819.8	763.3	12.0	107.6	81.4	15.0	>20	12T
3409	Ni-20Cr-25Fe-2ThO_2	689.5	630.2	16.0	100.6	89.6	7.0	20	3T

TABLE 79

MECHANICAL PROPERTIES OF TDNiCr BASE ALLOYS

Heat No.	Nominal Composition	Room Temperature UTS ksi	Room Temperature YS ksi	Room Temperature Elong. %	2000°F UTS ksi	2000°F YS ksi	2000°F Elong. %	2000°F 4500 psi S/R Hrs.	Trans. Bend Radius 105°
3335	Ni-16Cr-2ThO_2	125.1	105.9	26.0	14.5	14.5	8.0	>20	2T
3341	Ni-30Cr-2ThO_2	114.5	105.1	14.0	8.4	7.3	10.0	Failed on loading	4T
3336	Ni-16Cr-3.5Al-2ThO_2	162.6	122.4	11.5	13.0	11.6	5.5	>20	3T
3337	Ni-16Cr-4.5Al-2ThO_2	157.6	120.9	9.5	13.3	11.0	5.0	>20	3.5T
3338	Ni-16Cr-5.5Al-2ThO_2	154.3	142.1	10.1	12.2	11.9	7.5	>20	12T
3339	Ni-20Cr-4.5Al-2ThO_2	170.0	130.5	9.5	13.4	12.9	4.0	>20	5T
3340	Ni-20Cr-5.5Al-2ThO_2	172.0	145.4	7.5	14.4	11.4	6.0	6.2	>8T
3429	Ni-16Cr-5.5Al-0.2Y-2ThO_2	164.6	137.4	16.0	12.3	11.1	5.5	>20	7T
3351	Ni-16Cr-5.5Al-0.3La-2ThO_2	151.9	151.9	10.0	13.3	12.3	10.0	20	>11T
3352	Ni-16Cr-5.5Al-0.4Y-2ThO_2	149.0	111.5	10.0	12.5	10.4	10.0	>20	8T
3379	Ni-16Cr-5.5Al-0.5Th-2ThO_2	149.6	149.6	13.0	12.0	11.4	11.0	>20	8T
3380	Ni-20Cr-5.5Al-0.3La-2ThO_2	175.1	149.7	13.0	13.1	12.0	20.0	>20	8T
3381	Ni-20Cr-3.5Al-2ThO_2	154.8	117.5	8.5	14.7	13.3	4.0	>20	>6T
3388	Ni-30Cr-3.5Al-2ThO_2	170.4	169.4	13.0	13.6	11.3	11.0	0.9	8T
3389	Ni-20Cr-5.5Al-0.2Y-2ThO_2	173.9	142.2	10.0	12.7	11.9	11.0	0.1	10T
3577	Ni-4Cr-4Al-2ThO_2	103.7	88.9	15.0	14.0	11.3	15.0	>20	>9T
3579	Ni-4Cr-6Al-2ThO_2	119.7	97.7	16.0	14.0	12.4	11.2	>20	4T
3580	Ni-9Cr-4Al-2ThO_2	93.0	67.3	24.0	14.0	13.1	15.0	>20	7T
3582	Ni-9Cr-6Al-2ThO_2	118.9	110.7	12.0	15.6	11.8	15.0	>20	12T
3409	Ni-20Cr-25Fe-2ThO_2	100.0	91.4	16.0	14.5	13.0	7.0	20	3T

TABLE 79 (Cont'd)

MECHANICAL PROPERTIES OF TDNiCr BASE ALLOYS

Heat No.	Nominal Composition	Room Temperature UTS MN/m^2	Room Temperature YS MN/m^2	Room Temperature Elong. %	1093°C UTS MN/m^2	1093°C YS MN/m^2	1093°C Elong. %	1093°C 4500 psi S/R Hrs.	Trans. Bend Radius 105°
3410	Ni-20Cr-4Mn-2ThO_2	930.8	817.0	17.0	41.4	34.5	20.0	Failed on loading	3T
3412	Ni-20Cr-15Fe-2ThO_2	823.2	715.7	20.0	63.4	63.4	8.0	0.1	2T
3413	Ni-20Cr-15Fe-2Mn-2ThO_2	777.0	715.0	14.0	50.3	47.6	10.0	Failed on loading	4T
3350	Ni-30Cr-15Fe-2Mn-0.5Si-0.3La-2ThO_2	957.0	389.1	10.0	53.1	52.4	9.0	Failed on loading	10T
3391	Ni-16Cr-15Fe-2ThO_2	843.2	647.3	17.0	71.0	71.0	10.0	>20	2T
3392	Ni-20Cr-15Fe-2Mn-0.5Si-0.3La-2ThO_2	836.3	630.9	17.0	52.4	52.4	13.0	Failed on loading	3T
3399	Ni-16Cr-15Fe-2Mn-0.5Si-0.3La-2ThO_2	843.2	646.0	20.0	76.5	76.5	9.0	Failed on loading	3T
3390	Ni-23Cr-14Fe-1.5Al-0.2Si-2ThO_2	970.1	932.9	11.0	84.8	69.6	5.0	1.5	-

TABLE 79 (Cont'd)

MECHANICAL PROPERTIES OF TDNiCr BASE ALLOYS

Heat No.	Nominal Composition	Room Temperature UTS ksi	Room Temperature YS ksi	Room Temperature Elong. %	2000°F UTS ksi	2000°F YS ksi	2000°F Elong. %	2000°F 4500 psi S/R Hrs.	Trans. Bend Radius 105°
3410	Ni-20Cr-4Mn-2ThO_2	135.0	118.5	17.0	6.0	5.0	20.0	Failed on loading	3T
3412	Ni-20Cr-15Fe-2ThO_2	119.4	103.8	20.0	9.2	9.2	8.0	0.1	2T
3413	Ni-20Cr-15Fe-2Mn-2ThO_2	112.7	103.7	14.0	7.3	6.9	10.0	Failed on loading	4T
3350	Ni-30Cr-15Fe-2Mn-0.5Si-0.3La-2ThO_2	138.8	129.3	10.0	7.7	7.6	9.0	Failed on loading	10T
3391	Ni-16Cr-15Fe-2ThO_2	122.3	97.8	17.0	10.3	10.3	10.0	>20	2T
3392	Ni-20Cr-15Fe-2Mn-0.5Si-0.3La-2ThO_2	121.3	91.5	17.0	7.6	7.6	13.0	Failed on loading	3T
3399	Ni-16Cr-15Fe-2Mn-0.5Si-0.3La-2ThO_2	122.3	93.7	20.0	11.1	11.1	9.0	Failed on loading	3T
3390	Ni-23Cr-14Fe-1.5Al-0.2Si-2ThO_2	140.7	135.3	11.0	12.3	10.1	5.0	1.5	-

the minimum may be shifted and, accordingly, alloys of Ni-16Cr-2Al-2ThO_2 and Ni-16Cr-3Al-2ThO_2 require evaluation. Alloys of lower Cr content have low room temperature strength and alloys of higher Cr content, appear to be even more susceptible to γ' formation. (Heat 3388, Ni-30Cr-3.1Al-2ThO_2 showed considerable γ' after slow cooling from 1177°C (2150°F). An additional benefit may arise from lower Al contents in that it may be possible to achieve a larger grain size by processing at lower temperatures than before. In this manner elevated temperature strength could be improved.

h. Scale-Up Billet Processing

Fourteen scale-up billets were started during the Part I program to provide material for test evaluation. Three billets with reduced ThO_2 content and eleven alloy billets were made; all were 45.4 kg. (100 lb.) units. The alloys and the assigned heat numbers are shown in Table 80 along with processing information.

The three scale-up alloys (Heats 3553, 3554 and 3606) containing variations in thoria content of 1.0 and 1.5 percent rather than the standard 2.0 percent were roll consolidated and rolled to sheet. The sintering temperature and consolidation temperature were raised to 1177°C(2150°F) to obtain maximum reduction of Cr_2O_3. Fabrication of these heats to intermediate gauge plate and final sheet gauges of 0.038 cm. (0.015 in.) to 0.091 cm. (0.075 in.) were carried out utilizing standard procedures developed for TDNiCr sheet processing.

TABLE 80

TDNiCr BASE ALLOY SCALE-UP STUDIES

Heat No.	Composition	Sinter Temp. °C	Sinter Temp. °F	Consolidation Temp. Forge °C	Forge °F	Roll °C	Roll °F
3553	Ni-20Cr-1ThO_2	1177	2150			1177	2150
3606	Ni-20Cr-1ThO_2	1177	2150			1177	2150
3554	Ni-20Cr-1.5ThO_2	1177	2150			1177	2150
3504	Ni-16Cr-15Fe-2Mn 0.5Si-0.3La-2ThO_2	1066	1950	1066	1950		
3505	Ni-16Cr-3.5Al-0.2Y 2ThO_2	1066	1950	1204	2200		
3563	Ni-16Cr-3.5Al-2ThO_2	1066	1950			1204	2200
3564	Ni-20Cr-3.5Al-0.2Y 2ThO_2	1066	1950			1204	2200
3575	Ni-20Cr-3.5Al-2ThO_2	1066	1950			1204	2200
3738	Ni-16Cr-4.0Al-2ThO_2	1066	1950			1204	2200
3739	Ni-16Cr-4.5Al-2ThO_2	1066	1950			1204	2200
3740	Ni-16Cr-3.5Al-2ThO_2	1066	1950			1204	2200
3741	Ni-16Cr-3.5Al-0.2Y 2ThO_2	1066	1950			1204	2200
3771	Ni-16Cr-4.0Al-0.2Y 2ThO_2	1066	1950			1204	2200
3772	Ni-16Cr-4.0Al-1.5ThO_2	1066	1950			1204	2200

Mechanical properties were measured at various thicknesses ranging between 0.038 and 0.191 cm. (0.015 and 0.075 in.). These results are shown in Table 81. As indicated by these data, a decrease in thoria content from a nominal of 2.0 percent to either 1.5 or 1.0 percent appears to increase room and elevated temperature elongation and improve bend ductility without any great decrease in room and elevated temperature strengths. However, stress rupture results at 1093°C(2000°F) appear to be marginal, for material greater in thickness than 0.051 cm. (0.020 in.). Although ductility as indicated by elongation and bend testing may be enhanced by reducing thoria content, further evaluation of effect of thoria size as related to stress rupture and creep at various gauges must be carried out in an effort to optimize both strength and ductility. The ThO_2 content for TDNiCr for Part II will remain at 1.8-2.6%.

The first series of TDNiCr base scale-up billets included Heat 3504 a TDNiCr alloy containing Fe, Mn, Si and La. Heats 3505, 3563, 3564 and 3575 are the first TDNiCr base scale up alloy billets containing Al. The nominal compositions and process parameters are given in Table 80.

Heat 3504 was forge consolidated at 1066°C(1950°F), pickle decanned, conditioned, recanned in mild steel and rolled to 0.254 cm. (0.100 in.) intermediate gauge plate by the conventional TDNiCr process. Further processing to gauges of 0.127 cm. (0.050 in.) and 0.064 cm. (0.025 in.) was accomplished using TDNiCr processing techniques.

Heat 3505 was also pickle decanned and conditioned subsequent to forging. It was then recanned in a type 304 stainless steel can having 0.64 cm. (0.25 in.) thick cover plates and rolled to 0.64 cm. (0.25 in.) thick plate in three double passes with a reheat at 1204°C(2200°F) furnace temperature between each set of double passes. The resultant plate was mechanically stripped and hot sheared at 1204°C (2200°F) to remove tails and then cut into four equal segments approximately 22.86 cm. (9.0 in.) in length by plate width. One segment was retained at 0.64 cm. (0.25 in.) thickness. The remaining three segments were packed and recanned in type 304 stainless steel and rolled to yield three pieces approximately 0.25 cm. (0.10 in.) thick. One piece at this gauge was retained and the remaining two pieces were packed, canned and rolled to yield two pieces at approximately 0.64 cm. (0.025 in.) thick. Two of the three pieces were abrasive ground. One piece was held in the ground unrecrystallized state, while a second piece was subjected to a two hour heat treat at 1316°C(2400°F) and subsequently ground to a finish gauge of 0.038 cm. (0.015 in.) thickness. These two pieces were then submitted to NASA-Lewis for evaluation.

Heats 3563, 3564 and 3575 were all sintered at 1066°C (1950°F) and subsequently canned in conventional TDNiCr type roll consolidation cans employing aluminized steel slip sheets. Each unit was preheated in a hydrogen atmosphere for 2 hours at 1204°C(2200°F) and then roll consolidated.

TABLE 81

MECHANICAL PROPERTIES OF SCALE UP TDNiCr LOW ThO_2 ALLOYS

Heat No.	Gauge cm.	Room Temperature UTS MN/m^2	Room Temperature YS MN/m^2	Room Temperature Elong. %-cm.	1093°C UTS MN/m^2	1093°C YS MN/m^2	1093°C Elong. %-cm.	Stress Rupture 1093°C Hrs.	Stress Rupture 1093°C MN/m^2	Min. Bend	Nominal ThO_2 Content
3553	0.157	815.0	582.2	16.6	88.9	77.9	7.2	1.5	31.0	-	1.0%
	0.112	788.2	531.9	22.3	103.3	95.8	8.0	1.7	31.0	1.7T	1.0%
	0.076	757.2	513.3	21.2	104.0	95.1	4.6	1.5	31.0	0.5T	1.0%
	0.053	751.6	503.7	25.0	-	-	-	>20	31.0	1.0T	1.0%
3606	0.191	811.6	551.2	26.5	111.6	108.2	5.5	0.5	37.9	1.2T	1.0%
	0.127	808.2	565.7	23.5	115.1	110.9	5.0	0.5	37.9	1.2T	1.0%
	0.102	781.3	532.6	23.0	107.5	99.2	5.0	1.4	37.9	1.0T	1.0%
	0.076	797.2	541.6	25.2	110.2	107.5	5.0	0.4	37.9	1.2T	1.0%
	0.051	775.1	525.0	25.4	101.9	96.5	-	0.8	37.9	1.0T	1.0%
	0.038	844.7	604.3	30.0	105.4	99.2	6.0	>20	31.0	0.9T	1.0%
3554	0.178	815.1	534.7	26.2	108.2	101.9	3.8	2.1	31.0	-	1.5%
	0.114	801.9	505.7	26.2	93.7	85.4	5.0	4.8	31.0	1.8T	1.5%
	0.086	798.6	513.3	26.2	109.6	84.0	3.5	18.5	31.0	1.0T	1.5%
	0.053	772.4	613.2	26.7	105.4	97.1	4.0	>20	37.9	1.0T	1.5%

TABLE 81

MECHANICAL PROPERTIES OF SCALE UP TDNiCr LOW ThO_2 ALLOYS

Heat No.	Gauge in.	Room Temperature UTS ksi	Room Temperature YS ksi	Room Temperature Elong. %-in.	2000°F UTS ksi	2000°F YS ksi	2000°F Elong. %-in.	Stress Rupture 2000°F Time Hrs.	Stress Rupture 2000°F Stress psi	Min. Bend	Nominal ThO_2 Content
3553	0.062	118.3	84.5	16.6	12.9	11.3	7.2	1.5	4500	-	1.0%
	0.044	114.4	77.2	22.3	15.0	13.9	8.0	1.7	4500	1.7T	1.0%
	0.030	109.9	74.5	21.2	15.1	13.8	4.6	1.5	4500	0.5T	1.0%
	0.021	109.1	73.1	25.0	-	-	-	>20	4500	1.0T	1.0%
3606	0.075	117.8	80.0	26.5	16.2	15.7	5.5	0.5	5500	1.2T	1.0%
	0.050	117.3	82.1	23.5	16.7	16.1	5.0	0.5	5500	1.2T	1.0%
	0.040	113.4	77.3	23.0	15.6	14.4	5.0	1.4	5500	1.0T	1.0%
	0.030	115.7	78.6	25.2	16.0	15.6	5.0	0.4	5500	1.2T	1.0%
	0.020	112.5	76.2	25.4	14.8	14.0	-	0.8	5500	1.0T	1.0%
	0.015	122.6	87.7	30.0	15.3	14.4	6.0	>20	4500	0.9T	1.0%
3554	0.070	118.3	77.6	26.2	15.7	14.8	3.8	2.1	4500	-	1.5%
	0.045	116.4	73.4	26.2	13.6	12.4	5.0	4.8	4500	1.8T	1.5%
	0.034	115.9	74.5	26.2	15.9	12.2	3.5	18.5	4500	1.0T	1.5%
	0.021	112.1	89.0	26.7	15.3	14.1	4.0	>20	5500	1.0T	1.5%

The edge border weld on Heat 3563 broke on the initial consolidation and breakdown rolling passes thus requiring decanning at approximately 3.81 cm. (1.50 in.) in thickness. The edge borders were cropped to square the piece, it was recanned in type 304 stainless steel and rolled to a thickness of approximately 0.64 cm. (0.25 in.).

Heats 3564 and 3575 were each rolled all the way to 0.64 cm. (0.25 in.) in the original roll consolidation can. They were then pickle decanned and conditioned on a wide belt abrasive grinder.

Further rolling of Heats 3563, 3564 and 3575 consisted of pack rolling 0.64 cm. (0.25 in.) thick plates of each heat to an approximate gauge of 0.191 cm. (0.075 in.). At this stage of processing, segments of each heat were recanned in a pack configuration and rolled to about 0.064 cm. (0.025 in.) thickness. These sheets were conditioned, recrystallized at 1316°C(2400°F) and finally wide belt abrasive ground to finish.

Mechanical property data for the iron containing alloy (Heat 3504) and the four aluminum containing alloys (Heats 3505, 3563, 3564 and 3575) are shown in Table 82 for material at 0.038 cm. (0.015 in.) thickness. These data indicate that both the room temperature and high temperature properties of the TDNiCrAl alloys are similar to those of TDNiCr. The stress rupture values appear lower for the Fe containing alloy than for TDNiCr.

The six remaining alloys shown in Table 80 were additional scale-up alloys containing aluminum. They were compacted, sintered, roll consolidated, and hot rolled to an intermediate gauge of approximately 0.254 cm. (0.100 in.) in thickness during the Part I phase of the program. Work of these billets will be continued during Part II of this program.

i. TDNiCr Alloy System Selection

On the basis of oxidation resistance, the Ni-Cr-Al-ThO_2 system was superior to all other alloys evaluated. In addition the strength values obtained to date indicate that mechanical properties may be attained which are similar to those obtained with TDNiCr.

The basic alloy system which will be studied in Part II will be Ni-Cr-Al-ThO_2 plus the possible addition of yttrium. The alloy levels to be investigated have been narrowed to:

Cr	12 to 22%
Al	2 to 4%
Y	0 to 0.2%
ThO_2	1.5 to 2.5%

TABLE 82

MECHANICAL PROPERTIES OF SCALE UP TDNiCr BASE ALLOYS

Heat No.	Gauge cm.	Room Temperature UTS MN/m^2	Room Temperature YS MN/m^2	Room Temperature Elong. %-cm.	1093°C UTS MN/m^2	1093°C YS MN/m^2	1093°C Elong. %-cm.	Stress Rupture 1093°C 20 Hrs. @ 27.6 MN/m^2	Min. Bend
3504	0.038	762.7	524.3	11.0	118.5	109.6	6.0	Fail	1-1/2T
3505	0.038	630.4	362.4	20.5	78.5	71.7	7.0	OK	4T
3563	0.038	779.9	520.2	7.8	77.2	70.3	10.0	OK	3T
3564	0.038	928.8	618.7	10.0	90.3	84.1	7.5	OK	2T
3575	0.038	1002.4	619.4	16.0	84.0	77.9	6.0	OK	2T

TABLE 82

MECHANICAL PROPERTIES OF SCALE UP TDNiCr BASE ALLOYS

Heat No.	Gauge in.	Room Temperature UTS ksi	Room Temperature YS ksi	Room Temperature Elong. %-in.	2000°F UTS ksi	2000°F YS ksi	2000°F Elong. %-in.	Stress Rupture 2000°F 20 Hrs.@ 4500 psi	Min. Bend
3504	0.015	110.7	76.1	11.0	17.2	15.9	6.0	Fail	1-1/2T
3505	0.015	91.5	52.6	20.5	11.4	10.4	7.0	OK	4T
3563	0.015	113.2	75.5	7.8	11.2	10.2	10.0	OK	3T
3564	0.015	134.8	89.8	10.0	13.1	12.2	7.5	OK	2T
3575	0.015	145.5	89.9	16.0	12.2	11.3	6.0	OK	2T

SUMMARY OF RESULTS

The goals of the Part I program have been met and exceeded. Processes have been developed and TDNiCr sheet and foil have been manufactured and delivered to NASA Centers for further studies. A new alloy matrix has been developed which offers outstanding oxidation resistance.

A standard process has been established for the production of TDNiCr sheet for the gauge range 0.025-0.102 cm. (0.010-0.040 in.). Sheet is being produced to 46 cm. wide x 91 cm. long (18 x 36 in.) minimum sizes in all gauges.

TDNiCr sheet produced by the standard process meets the requirements of Fansteel Specifications S-TC-S-01-R-1, dated December 1, 1969 and S-DMM-S-01-R-0, dated January 1, 1969.

The standard process includes the following steps:

(a.) Powder Manufacture

- Ni-20Cr-2ThO_2 - Nominal Composition
- ThO_2 size determination

(b.) Hydrostatic Compaction

- Rubber boot - No Mylar liner - Metal mesh container - 414 MN/m^2 (60,000 psi)
- 45.4 kg. (100 lb.) Unit 8.25 x 21.59 x 46.99 cm. (3-1/4 x 8-1/2 x 18-1/2 in.) - Nominal

(c.) Sinter

- 954°C(1750°F) in dry H_2 - Compact in mild steel can
- Dew point controlled to -57°C(-70°F) or better

(d.) Consolidate

- Roll to 2.54 cm. (1.0 in.) thickness Aluminized steel slip sheets
- Preheat canned unit to 1010°C(1850°F) in H_2 at dew point of -57°C(-70°F) or better, minimum of two hours - maximum of three hours

(e.) Decan and Condition

- Saw crop edges and ends as required
- Mill, shape and/or grind surfaces as required
- Sample - ThO_2 size check

  (<15μ-Heat treat 2.54 cm. (1.0 in.) slab @ 1093°C(2000°F) for 2 hours)

  (>15μ, inclusive - No heat treat required)

(f.) Recan

- Mild steel

(g.) Roll to Intermediate Plate

- Preheat to 760°C(1400°F)
- Roll from 2.54 to 0.254 cm. (1.0 to 0.1 in.) (Recrystallize sample at 1177°C(2150°F) for two hours)

(h.) Decan, grind condition, chemical clean

(i.) Rolling to Gauge

- Recan in either 0.160 cm. (0.063 in.) or 0.180 cm. (0.071 in.) Armco Aluminized steel Type 1 or equivalent
- Preheat units to warm rolling temperatures of 760°C +0° -54°C (1400°F +0° -100°F)
- Isothermally roll to gauge

(j.) Condition

- Chemical clean
- Grind and/or belt sand condition

(k.)

- Recrystallize heat treatment - Program heat up to 1177°C(2150°F)/2 hours.
- Dry hydrogen atmosphere

(l.) Finishing - Gauges of 0.038 cm. (0.015 in.) and greater

- Roll level if required
- Wide belt abrasive grind to 32 rms or better

(m.) Finishing - Gauges of 0.025 cm. (0.010 in.) but less than 0.038 cm. (0.015 in.)

- Wide belt abrasive polish to 32 rms or better
- In process inspection for gauge and finish
- Shear

  Shear to square edges and/or ends
- Degrease

- Cold Roll

  Tension roll a maximum of 5% reduction
- Degrease
- Heat Treatment

  Program heat up to 1177°C(2150°F) for 2 hours

  Dry hydrogen atmosphere

(n.) Shear to Size

- In process inspection for gauge and finish
- Shear to finish size
- Sample

(o.) Inspection

- Inspect size, gauge, finish, flatness
- Test to specification

(p.) Ship

A reproducibility evaluation was conducted on three heats of TDNiCr. Three gauges were evaluated for each of the three heats; 0.025, 0.051 and 0.076 cm. (0.010, 0.020 and 0.030 in.). The data indicate that the proposed gauge tolerances can be readily met and that a weight tolerance of +5% can also be attained at all of the gauges. Chemistry, size, flatness and surface finish can all be reproduced. Extensive mechanical testing demonstrated that strength and bend specifications can be attained. However, control of the absolute grain size and hence spread in properties has not yet been attained, particularly at gauges of 0.076 cm. (0.030 in.) and larger.

A total of 821.1 kg. (1808.6 lb.) of TDNiCr sheet was shipped to NASA designated locations. The sheet will be used for technology and hardware programs to be conducted by NASA Centers and on NASA sponsored space shuttle contracts. The gauges ranged from 0.025-0.70 cm. (0.010-0.275 in.). The sheet was manufactured from fifty-two - 45.4 kg. (100 lb.) units and seven - 68.0 kg. (150 lb.) units. The overall yield of slightly less than 30% is not representative since some of the material from the 59 heats was utilized for process studies. Actual yields by the standard process were a function of gauge and ranged from 35% for 0.025 cm. (0.010 in.) sheet to 44% for 0.076 cm. (0.030 in.) sheet.

Several approaches have been followed to develop foil capability for TDNiCr. High strength foil can be produced by warm pack rolling however cold finishing is required to obtain adequate surface finish and appearance. High quality foil in gauges from 0.005-0.013 cm. (0.002-0.005 in.) has been fabricated by cold tension rolling on a Sendzimir mill. Elevated temperature strengths are less than for warm rolled material but bend ductility is excellent.

Foil studies will be continued on Part II and the concept of cold tension rolling of sheet only partially warm rolled will be studied for gauges of 0.025 cm. (0.010 in.) and higher.

Process studies have shown that an input unit larger than 45.4 kg. (100 lb.) is required to produce the goal sizes of sheet, 61 x 152 cm. (24 x 60 in.), in all gauges.

Development studies on a 68.0 kg. (150 lb.) unit were initiated in Part I and will be continued in Part II.

Process improvement studies have been made to upgrade the quality and the mechanical properties of the sheet. Improved dimensional tolerances, weight tolerances, flatness and surface finish all appear feasible. The increased sheet size, 61 x 152 cm. (24 x 60 in.), can be achieved with 68.0 kg. (150 lb.) input units however, reproducibility of properties has not been demonstrated and the yield of product was reduced. These studies will be continued in Part II.

Two special purpose furnaces were designed and built for use in the process improvement studies. A warm rolling oven was built by Trent Inc. that would permit isothermal rolling of scaled up TDNiCr sheet in the temperature range of 538 to 871°C (1000-1600°F). A second furnace built by Pereny was designed to permit the combination of two process steps, sintering of a hydrostatically compacted billet, and the heat up for consolidation by rolling.

The basic composition of TDNiCr alloy was studied by investigating various values for the chromium and ThO_2 levels. The alloy range for continuation in Part II will be:

ThO_2	1.8 to 2.6%
Chromium	18.5 to 20.5%

A series of minor alloy studies were made to try to improve the ductility behavior of TDNiCr at both ambient and elevated temperatures. Hydride and halide additions offer

some promise and will be further explored in Part II. Reactive element and rare earth additions did not afford any improvements. Reductions in ThO_2 content resulted in increased ductility but at the expense of strength. Lower ThO_2 values will be considered further only for foil applications.

Severe oxidation tests simulating space shuttle conditions indicate that standard TDNiCr may not have the desired oxidation resistance over the whole temperature range from 982-1204°C(1800-2200°F). An alloy program was aimed at modifying the base composition to further improve its oxidation resistance without seriously impairing other prerequisite properties.

Two general approaches were followed, one was to alloy the TDNiCr with elements which tend to form complex oxides or spinels with Cr_2O_3. One alloy of this type containing Fe, Mn, Si, and La showed considerable improvement in oxidation behavior.

The second approach was the utilization of Al in the nickel-chromium alloy matrix. With this system the formation of Cr_2O_3 is suppressed in favor of the non-volatile Al_2O_3 and $NiAl_2O_4$ species. Alloy studies indicated that a minimum of 3 percent Al would provide cyclic oxidation protection under the most severe test conditions at temperatures up to 1260°C(2300°F).

Limited scale up studies and mechanical property testing indicate that sheet can be manufactured in the gauge ranges of interest with mechanical properties similar to those obtained with TDNiCr.

The basic alloy system which has been chosen for further study in Part II will be Ni-Cr-Al-ThO_2 alloys plus the possible addition of yttrium. The alloy levels to be investigated have been narrowed to:

Cr	12 to 22%
Al	2 to 4%
Y	0 to 0.2%
ThO_2	1.5 to 2.5%

PRECEDING PAGE BLANK NOT FILMED

APPENDIX A

FANSTEEL PRODUCT SPECIFICATIONS

Preceding page blank

853-75
FANSTEEL INC.
Metals Division
5101 TANTALUM PLACE
BALTIMORE, MARYLAND 21226
Phone: 301/355-0600 TWX: 710/234-3496

TECHNICAL DATA BULLETIN

METALS DIVISION

December 1, 1969
S-TC-S-01-R-1

FANSTEEL PRODUCT SPECIFICATION

Thoriated Nickel Base Alloys

Composition and Properties

TD Nickel Chromium Sheet

Nickel - 20 Chromium - 2 Thoria

1. Scope

1.1 This specification covers composition and property requirements for Fansteel TDNiCr.

1.2 TDNiCr sheet shall conform to the surface and dimensional requirements of S-DMM-S-01-R-0, except that the uniform structure requirement of that specification shall not be construed as applying to the appearance of chromium oxide as seen in a micro.

2. Chemical Composition

2.1 The chemical composition, as determined by Fansteel standard analytical procedures, shall conform to the following limits:

Constituent	Minimum Weight Percent	Maximum Weight Percent	Check Analysis Weight Percent
Thoria (ThO_2)	1.50	3.00	±0.1
Chromium	18.00	22.00	±0.2
Carbon		0.05	±0.005
Sulfur		0.015	±0.002
Nickel	By Difference		

Check analysis limits provide for sampling and between laboratory variability. Customer analyses which differ from the specification limits by less than the check analysis tolerance shall not be cause for rejection.

3. Mechanical Properties

3.1 Room Temperature Tensile Properties: Sheet supplied under this specification shall conform to the following minimum requirements when tested at room temperature transverse to the final rolling direction in accordance with the procedures described in Section 4.1.

Thickness Inches	Ultimate Tensile Strength PSI, Min.	0.2% Offset Yield Strength PSI, Min.	Elongation In 1 Inch Percent Min.
0.020 to 0.075, incl.	110,000	75,000	10
0.010 to less 0.020	100,000	65,000	8

3.2 Elevated Temperature (2000°F in air) Tensile Properties: Sheet supplied under this specification shall conform to the following minimum requirements when tested at 2000°F in air transverse to the final rolling direction in accordance with the procedures described in Section 4.2.

Thickness Inches	Ultimate Tensile Strength PSI, Min.	0.2% Offset Yield Strength PSI, Min.	Elongation in 1 Inch Percent Min.
0.020 to 0.075, incl.	15,000	to be reported	1%
0.010 to less 0.020	10,000	to be reported	1%

3.3 Stress Rupture (2000°F in air) Properties: Sheet supplied under this specification shall conform to the following minimum requirements when tests transverse to the direction of final rolling in air at 2000°F in accordance with the procedure described in Section 4.3.

Thickness Inches	Stress PSI	Life-hours	Elongation in 1 Inch Percent Min.
0.020 to 0.075, incl.	5,500	20	to be reported
0.010 to less 0.020	4,000	20	to be reported

3.4 Bend Test: Material shall withstand, without cracking, bending at room temperature through an angle of 105 degrees around a radius equal to the bend factor times the nominal thickness of the material, with axis of bend parallel to the direction of rolling, and with axis of bend perpendicular to the direction of rolling. Bend test specimens shall be prepared by polishing the surfaces and edges through 240 and 400 grit papers. Surface roughening resulting from orange peel effect shall not be cause for rejection.

Nominal Thickness (Inches)	Bend Factor
0.020 to 0.075, incl.	3.0
0.010 to less 0.020	3.0

4. Test Methods

4.1 Room Temperature Tensile Testing: A representative specimen from each compaction and nominal gage shall be prepared and tested in conformity with the Tentative Methods of Tension Testing of Metallic Materials, ASTM E8-57T. The specimen tested shall have a one-inch gage length and a one-quarter inch gage width. Tensile properties shall be determined using a controlled strain rate of 0.0005 ±0.002 in./in./min. through 0.6% offset, then 0.05 ±0.02 in./in./min. to failure. Specimens shall be taken transverse to the final rolling direction. Tensile tests shall be conducted at a temperature between 65°F and 85°F.

4.2 Elevated Temperature Tensile Testing: Representative specimens from each compaction and nominal gage shall be prepared and tested in conformity with ASTM E21 - latest revision except as noted below. The specimens tested shall have a one-inch gage length and one-quarter inch gage width. Tensile properties shall be determined using a controlled cross-head speed of 0.05 ±0.02 in./in./min. to failure. One specimen shall be taken transverse to the direction of final rolling.

4.3 Stress Rupture Testing: Representative specimens from each compaction and nominal gage shall be prepared and tested in conformity with ASTM E139 - latest revision, except as noted below. The specimens tested shall have a one-inch gage length and a one-quarter inch gage width. Temperature shall be continuously recorded by means of one thermocouple attached to the gage section of the specimen. One specimen shall be taken transverse to the direction of final rolling. After 20 hours, stress may be increased in increments of 1000 psi per hour to failure in order to determine elongation.

853-75

FANSTEEL INC.
Metals Division
5101 TANTALUM PLACE
BALTIMORE, MARYLAND 21226
Phone: 301/355-0600 TWX: 710/234-2496

TECHNICAL DATA BULLETIN

METALS DIVISION

January 1, 1969
S-DMM-S-01-R-0

THORIATED NICKEL BASE ALLOYS

GENERAL - ALL ALLOYS - SHEET

1. Scope

   1.1 This specification covers surface and dimensional requirements for all Fansteel thoriated nickel alloys in sheet form.

2. Quality

   2.1 Micro or metallographic examination shall reveal a substantially uniform structure. Material shall be essentially free of porosity. Standards for acceptance or rejection shall be as agreed upon by purchaser and vendor.

3. Structural Condition

   3.1 Material will normally be supplied in the stress relieved condition.

4. Surface Finish

   4.1 Material may be supplied with a cold-rolled (and heat-treated), pickled, or polished surface.

   4.2 Surface defects may be removed by such methods as grinding, buffing, or polishing.

   4.3 By visual inspection, the material shall be free of any evidence of contamination. Differences in reflectivity shall not be considered evidence of contamination.

   4.4 No pits which reduce the thickness of the material below the minimum thickness specification are acceptable. Occasional pits of less than this depth are acceptable provided the number is not in excess of five per square foot. Individual pits or roughened areas which appear

under magnification as a scattering of pits shall be acceptable if not of measurable depth mechanically (i.e., are less than 0.0005" in depth as determined optically by the light section method). There is no restriction on the number of pits of this type which may be present.

4.5 No mars, gouges, scratches, or similar defects which reduce the thickness of the material below the minimum thickness specification are acceptable. Occasional defects of this type less than this depth are acceptable provided the number is not in excess of five per square foot.

Superficial scratches of a depth not measurable mechanically (i.e., less than 0.0005" in depth as determined optically by the light section method) shall not be cause for rejection in any number.

5. Dimensional Tolerances

5.1 Thickness Tolerances:

Thickness (Inches)	Thickness Tolerance (Inches)
0.006 to 0.010, incl.	±0.0015
Over 0.010 to 0.025, incl.	±0.002
Over 0.025 to 0.034, incl.	±0.003
Over 0.034 to 0.056, incl.	±0.004
Over 0.056 to 0.070, incl.	±0.005
Over 0.070 to 0.078, incl.	±0.006
Over 0.078 to 0.109, incl.	±0.007
Over 0.109 to 0.140, incl.	±0.008
Over 0.140 to 0.171, incl.	±0.009
Over 0.171 to 0.187, incl.	±0.010

In accordance with standard commercial practice, thickness measurements are taken at least 3/8" from the edge of the sheet.

5.2 Width Tolerance:

Width (Inches)	Width Tolerance (Inches)
Up to 28" incl.	+ 1/8, -0

5.3 Length Tolerance:

Length (Inches)	Length Tolerance (Inches)
Up to 96" incl.	+ 1/8, -0

5.4 Flatness Tolerance: The maximum deviation from flatness shall not exceed 8% as calculated from the following formula:

$$\frac{H}{L} \times 100 = \% \text{ Flatness Deviation}$$

Where: H = Maximum vertical distance between a flat reference surface and the lower surface of the sheet;

L = Minimum horizontal distance between the high point on the sheet where H is determined and the point where the lower surface of the sheet touches the reference surface.

A value of H less than 1/16" shall not be cause for rejection.

The maximum deviation from flatness shall not exceed 2", independent of span, as measured with the sheet resting concave side down on a flat reference surface.

6. Marking

6.1 Unless otherwise specified, each sheet shall be marked with Fansteel alloy identification, compaction number, and nominal thickness in inches. The characters shall be at least 3/8" in height and applied with a marking fluid removable by cleaning solution. The rows shall be alternately staggered and spaced not more than three inches apart. Direction of final rolling shall be marked.

7. Packaging

7.1 Sheet shall be protected by interleaving with paper between each sheet and the next. Material is normally packaged in wooden boxes reinforced with steel strapping. Small orders may be packaged with corrugated paper stiffeners and Kraft paper wrapping.

7.2 Markings on the outside of the package shall include customer's name and purchase order number and Fansteel thoriated nickel alloy designation.

8. Reports

8.1 Each shipment shall be accompanied by a shipping memorandum which reports the customer purchase order number, alloy identification number, and size of pieces, heat number and weight.

8.2 Each shipment shall be accompanied by three copies of a test report giving the customer purchase order number, alloy identification, specification number, compaction number, chemical composition, structural condition, and mechanical properties.

9. Rejection

9.1 Fansteel must be notified in writing of all rejection claims within ninety days of receipt of material. This notice should contain the purchase order number, compaction number, size, weight, number of pieces rejected, and detailed reasons for rejecting claims. Fansteel shall have the opportunity of inspecting this material, at the customer's plant to determine the validity of the rejection claim. Upon authorization by Fansteel, the rejected material shall be returned as directed at the expense of Fansteel.

10. Shipping Tolerance

10.1 A shipping weight tolerance of $\pm$10% of ordered weight shall apply.

APPENDIX B

METALLOGRAPHIC TECHNIQUES

Preparation of Metallographic Samples

Metallographic examination by light microscopy was conducted on samples prepared by the following steps:

- Mount in Bakelite powder
- Progressively wet sand through 120, 240, 400 and 600 grit silicon carbide papers
- Pre-polish with six micron diamond paste (Metadi) on nylon cloth
- Polish with one micron paste (Metadi) on microcloth
- Final polish on vibratory polishing machine using Gamal polishing cloth with a slurry of gamma alumina (0.05 micron alumina in water)
- Electrolytically etch tantalum sheet cathode 4 volts D.C. at 4-5 sec. intervals until grain boundaries are developed.

  Etch solution

70 ml	CH_3OH
20 ml	Glycerol
10 ml	HNO_3

- Swab with lactic acid
- Rinse in warm running water, rinse in methanol, dry in hot air stream.

Electron Microscopy

Electron microscopy replicas were prepared for examination of ThO_2 and Cr_2O_3 particle size and distribution. The replicas were examined on a Bendix Transcope at magnifications of 5,000X and 10,000X.

The samples were prepared as for light microscopy.

Collodion replicas shadowed with chromium at 30° were used. Second and third replicas are normally used to minimize pick-up of extracted particles from the preparation techniques.

Prints of as-polished samples show ThO_2 and Cr_2O_3 as "white or light gray" particles; black particles are extracted particles which adhered to the collodion.

Etched samples may also be replicated but the distribution of the ThO_2 and Cr_2O_3 particles is distorted by the etching reactions.

Grain Size Determination

The grain shapes in TDNiCr sheet are lenticular and are best described by their average grain diameter and grain aspect ratio (ratio of grain length to grain thickness). The line intercept technique was used to measure these numbers. This technique* involves taking a photomicrograph of a sample, drawing horizontal and vertical lines of equal length on it, and counting the number of intersections of lines with grain boundaries. The formulae used to calculate average grain diameter and aspect ratio are:

Average Grain Diameter: $D = L/(Nt \times M)$

where
- D = Avg. grain diameter
- L = Total length of lines on photomicrograph
- Nt = Total number of grain boundary intersections
- M = Magnification

Grain Aspect Ratio: $\alpha = \frac{Nv}{Nh}$

where
- α = G.A.R. = Ratio of grain length to grain thickness
- Nv = No. of intersections of vertical lines with grain boundaries
- Nh = No. of intersections of horizontal lines with grain boundaries

Nh and Nv must be obtained over the same total length.

---

*G. E. Dieter, Mechanical Metallurgy, 1961.

The grain diameters reported are the average of two locations each for the longitudinal direction and the transverse direction. Grain diameters of 0.025 to 0.102 cm. (0.010 to 0.040 in.) sheet range from 0.030 mm to 0.200 mm and depend primarily on the gauge. There is no difference in grain diameter when viewed in either a longitudinal or transverse micro. Grain aspect ratios are 2.0-5.5.

ThO_2 Size Determination

The average ThO_2 size was determined by the x-ray line broadening technique. Nickel filtered CuK_x radiation was used on the lll reflection. The ThO_2 size is calculated from the line breadth at the half intensity position.

The samples are prepared by mounting a cut section in sample holder and polishing through 400 grit silicon carbide papers.

APPENDIX C

REPRODUCIBILITY TEST DATA

TABLE C-1

REPRODUCIBILITY TENSILE TEST DATA

Heat No.	Sheet No.	Gauge cm.	Gauge in.	Sample No.	Direction	Test Temp. °C	Test Temp. °F	UTS MN/m²	UTS ksi	YS MN/m²	YS ksi	Elong. %
3415-11		0.076	0.030	A	T	Room	Room	817.8	118.7	562.2	81.6	20.0
3415-11		0.076	0.030	D	T	Room	Room	799.2	116.0	541.6	78.6	18.2
3415-11		0.076	0.030	P	T	Room	Room	811.0	117.7	548.0	79.1	20.8
3415-11		0.076	0.030	S	T	Room	Room	796.5	115.6	529.8	76.9	18.4
3415-11		0.076	0.030	1	T	Room	Room	835.1	121.2	564.3	81.9	25.0
3415-11		0.076	0.030	2	T	Room	Room	857.8	124.5	560.8	81.4	21.0
3415-11		0.076	0.030	109	T	Room	Room	875.0	127.0	568.4	82.5	22.0
3415-12		0.076	0.030	A	T	Room	Room	800.6	116.2	540.2	78.4	20.0
3415-12		0.076	0.030	D	T	Room	Room	820.6	119.1	549.1	79.7	22.5
3415-12		0.076	0.030	P	T	Room	Room	789.6	114.6	575.3	83.5	20.0
3415-12		0.076	0.030	S	T	Room	Room	802.0	116.4	533.3	77.4	20.0
3415-11		0.076	0.030	H	L	Room	Room	865.4	125.6	558.8	81.1	18.4
3415-11		0.076	0.030	K	L	Room	Room	858.5	124.6	549.8	79.8	18.0
3415-11		0.076	0.030	N	L	Room	Room	867.5	125.9	560.2	81.3	17.5
3415-11		0.076	0.030	U	L	Room	Room	869.5	126.2	558.8	81.1	17.7
3415-11		0.076	0.030	X	L	Room	Room	870.2	126.3	576.0	83.6	17.5
3415-11		0.076	0.030	AA	L	Room	Room	864.0	125.4	573.2	83.2	17.0
3415-11		0.076	0.030	29	L	Room	Room	833.0	120.9	551.2	80.0	12.5
3415-11		0.076	0.030	30	L	Room	Room	916.4	133.0	583.6	84.7	15.0
3415-11		0.076	0.030	105	L	Room	Room	904.0	131.2	580.1	84.2	14.0
3415-11		0.076	0.030	112	L	Room	Room	885.4	128.5	585.7	85.0	11.0
3415-12		0.076	0.030	H	L	Room	Room	859.9	124.8	561.5	81.5	16.0
3415-12		0.076	0.030	K	L	Room	Room	861.9	125.1	555.3	80.6	17.0
3415-12		0.076	0.030	N	L	Room	Room	857.8	124.5	554.6	80.5	18.5
3415-12		0.076	0.030	U	L	Room	Room	789.6	114.6	575.3	83.5	20.0
3415-12		0.076	0.030	X	L	Room	Room	868.8	126.1	565.0	82.0	17.4
3415-12		0.076	0.030	AA	L	Room	Room	865.4	125.6	549.1	79.7	17.5
3415-11		0.076	0.030	35	45°	Room	Room	839.2	121.8	569.8	82.7	17.0
3415-11		0.076	0.030	36	45°	Room	Room	839.2	121.8	565.7	82.1	19.0

TABLE C-2

REPRODUCIBILITY TENSILE TEST DATA

Heat No.	Sheet No.	Gauge cm.	Gauge in.	Sample No.	Direction	Test Temp. °C	Test Temp. °F	UTS MN/m^2	UTS ksi	YS MN/m^2	YS ksi	Elong. %
3415-11		0.076	0.030	3	T	204	400	784.1	113.8	526.4	76.4	20.0
3415-11		0.076	0.030	4	T	204	400	769.6	111.7	505.7	73.4	20.0
3415-11		0.076	0.030	5	T	427	800	662.8	96.2	442.3	64.2	20.0
3415-11		0.076	0.030	6	T	427	800	702.1	101.9	484.4	70.3	18.5
3415-11		0.076	0.030	7	T	649	1200	421.0	61.1	350.7	50.9	7.5
3415-11		0.076	0.030	8	T	649	1200	408.6	59.3	345.9	50.2	5.0
3415-11		0.076	0.030	9	T	871	1600	228.7	33.2	224.6	32.6	4.0
3415-11		0.076	0.030	10	T	871	1600	241.8	35.1	237.0	34.4	5.0
3415-11		0.076	0.030	11	T	982	1800	164.0	23.8	160.5	23.3	5.0
3415-11		0.076	0.030	12	T	982	1800	161.2	23.4	157.1	22.8	5.0
3415-11		0.076	0.030	129	L	982	1800	174.3	25.3	170.9	24.8	6.0
3415-11		0.076	0.030	130	L	982	1800	179.1	26.0	171.6	24.9	8.0
3415-11		0.076	0.030	114	45°	982	1800	171.6	24.9	171.6	24.9	5.0
3415-11		0.076	0.030	115	45°	982	1800	163.3	23.7	161.2	23.4	4.5
3415-11		0.076	0.030	13	T	1093	2000	141.9	20.6	132.3	19.2	7.5
3415-11		0.076	0.030	14	T	1093	2000	137.8	20.0	137.8	20.0	5.0
3415-11		0.076	0.030	110	T	1093	2000	138.5	20.1	138.5	20.1	4.0
3415-11		0.076	0.030	B	T	1093	2000	126.8	18.4	124.0	18.0	2.6
3415-11		0.076	0.030	E	T	1093	2000	119.2	17.3	116.4	16.9	2.4
3415-11		0.076	0.030	Q	T	1093	2000	129.5	18.8	129.5	18.8	1.9
3415-11		0.076	0.030	T	T	1093	2000	126.1	18.3	126.1	18.3	1.5
3415-12		0.076	0.030	B	T	1093	2000	126.8	18.4	126.8	18.4	1.5
3415-12		0.076	0.030	E	T	1093	2000	126.1	18.3	126.1	18.1	2.1
3415-12		0.076	0.030	Q	T	1093	2000	124.7	18.1	126.1	18.1	2.0
3415-12		0.076	0.030	T	T	1093	2000	128.2	18.6	128.2	18.6	1.5
3415-11		0.076	0.030	31	L	1093	2000	152.3	22.1	150.2	21.8	4.0
3415-11		0.076	0.030	32	L	1093	2000	138.5	20.1	137.1	19.9	3.0
3415-11		0.076	0.030	106	L	1093	2000	148.8	21.6	142.5	20.7	5.0
3415-11		0.076	0.030	113	L	1093	2000	143.3	20.8	140.0	20.3	5.5
3415-11		0.076	0.030	I	L	1093	2000	130.9	19.0	130.9	19.0	2.2

TABLE C-3

REPRODUCIBILITY TENSILE TEST DATA

Heat No.	Sheet No.	Gauge cm.	Gauge in.	Sample No.	Direction	Test Temp. °C	Test Temp. °F	UTS MN/m^2	UTS ksi	YS MN/m^2	YS ksi	Elong. %
3415-11		0.076	0.030	L	L	1093	2000	130.2	18.9	129.5	18.8	2.5
3415-11		0.076	0.030	O	L	1093	2000	131.6	19.1	131.6	19.1	2.3
3415-11		0.076	0.030	V	L	1093	2000	132.3	19.2	131.6	19.1	3.3
3415-11		0.076	0.030	Y	L	1093	2000	130.2	18.9	130.2	18.9	3.6
3415-11		0.076	0.030	BB	L	1093	2000	131.6	19.1	128.8	18.7	2.8
3415-12		0.076	0.030	I	L	1093	2000	133.0	19.3	133.0	19.3	2.4
3415-12		0.076	0.030	L	L	1093	2000	137.8	20.0	137.1	19.9	3.3
3415-12		0.076	0.030	O	L	1093	2000	135.7	19.7	133.7	19.4	2.7
3415-12		0.076	0.076	V	L	1093	2000	137.1	19.9	135.7	19.7	2.5
3415-12		0.076	0.030	Y	L	1093	2000	133.0	19.3	133.0	19.3	2.0
3415-12		0.076	0.030	BB	L	1093	2000	143.3	20.8	143.3	20.8	2.6
3415-11		0.076	0.030	37	45°	1093	2000	142.6	20.7	141.2	20.5	3.5
3415-11		0.076	0.030	38	45°	1093	2000	144.0	20.9	141.2	20.5	4.5
3415-11		0.076	0.030	15	T	1204	2200	83.4	12.1	83.4	12.1	1.8
3415-11		0.076	0.030	16	T	1204	2200	91.6	13.3	89.6	13.0	2.5
3415-11		0.076	0.030	131	L	1204	2200	93.0	13.5	93.0	13.5	3.0
3415-11		0.076	0.030	132	L	1204	2200	102.7	14.9	100.6	14.6	2.5
3415-11		0.076	0.030	116	45°	1204	2200	93.0	13.5	93.0	13.5	2.5
3415-11		0.076	0.030	117	45°	1204	2200	90.9	13.2	88.2	12.8	5.0
3415-11		0.076	0.030	141	T	1316	2400	53.1	7.7	45.5	6.6	2.0
3415-11		0.076	0.030	142	T	1316	2400	49.5	7.2	48.9	7.1	2.0

TABLE C-4

REPRODUCIBILITY TENSILE TEST DATA

Heat No.	Sheet No.	Gauge cm.	Gauge in.	Sample No.	Direction	Test Temp. °C	Test Temp. °F	UTS MN/m^2	UTS ksi	YS MN/m^2	YS ksi	Elong. %
3415-16		0.025	0.010	A	T	Room	Room	793.7	115.2	593.2	86.1	20.5
3415-16		0.025	0.010	D	T	Room	Room	787.5	114.3	599.4	87.0	15.0
3415-16		0.025	0.010	P	T	Room	Room	792.4	115.0	595.7	85.0	15.5
3415-16		0.025	0.010	S	T	Room	Room	779.3	113.1	592.5	86.0	15.0
3415-16		0.025	0.010	1	T	Room	Room	742.7	107.8	572.6	83.1	11.5
3415-16		0.025	0.010	2	T	Room	Room	780.6	113.3	606.3	88.0	15.0
3415-16		0.025	0.010	109	T	Room	Room	775.8	112.6	599.4	87.0	10.0
3415-17		0.025	0.010	A	T	Room	Room	804.8	116.8	616.7	89.5	12.0
3415-17		0.025	0.010	D	T	Room	Room	828.2	120.2	661.4	96.0	20.0
3415-17		0.025	0.010	P	T	Room	Room	812.3	117.9	622.9	90.4	15.0
3415-17		0.025	0.010	S	T	Room	Room	820.6	119.1	667.6	96.9	6.5
3415-16		0.025	0.010	H	L	Room	Room	751.0	109.0	677.3	98.3	3.5
3415-16		0.025	0.010	K	L	Room	Room	792.4	115.0	678.0	98.4	7.0
3415-16		0.025	0.010	N	L	Room	Room	778.6	113.0	658.0	95.5	6.5
3415-16		0.025	0.010	U	L	Room	Room	-	(2)	-	-	-
3415-16		0.025	0.010	X	L	Room	Room	780.6	113.3	654.6	95.0	5.7
3415-16		0.025	0.010	AA	L	Room	Room	784.1	113.8	630.4	91.5	5.0
3415-16		0.025	0.010	29	L	Room	Room	749.6	108.8	637.3	92.5	2.5
3415-16		0.025	0.010	30	L	Room	Room	824.7	119.7	621.5	90.2	10.0
3415-16		0.025	0.010	105	L	Room	Room	878.5	127.5	658.7	95.6	10.0
3415-16		0.025	0.010	112	L	Room	Room	761.3	110.5	648.3	94.1	5.1
3415-17		0.025	0.010	H	L	Room	Room	774.4	112.4	658.7	95.6	5.0
3415-17		0.025	0.010	K	L	Room	Room	917.7	133.2	659.4	95.7	11.5
3415-17		0.025	0.010	N	L	Room	Room	835.1	121.2	683.5	99.2	6.5
3415-17		0.025	0.010	U	L	Room	Room	722.1	104.8	620.1	90.0	4.5
3415-17		0.025	0.010	X	L	Room	Room	815.1	118.3	680.7	98.8	6.0
3415-17		0.025	0.010	AA	L	Room	Room	840.6	122.0	686.2	99.6	5.0
3415-16		0.025	0.010	35	45°	Room	Room	762.7	110.7	573.2	83.2	7.5
3415-16		0.025	0.010	36	45°	Room	Room	773.1	112.2	621.5	90.2	10.2

TABLE C-5

REPRODUCIBILITY TENSILE TEST DATA

Heat No.	Sheet No.	Gauge cm.	Gauge in.	Sample No.	Direction	Test Temp. °C	Test Temp. °F	UTS MN/m²	UTS ksi	YS MN/m²	YS ksi	Elong. %
3415-16		0.025	0.010	3	T	204	400	-	(2)	-	-	-
3415-16		0.025	0.010	4	T	204	400	-	(2)	-	-	-
3415-16		0.025	0.010	5	T	427	800	-	(2)	-	-	-
3415-16		0.025	0.010	6	T	427	800	-	(2)	-	-	-
3415-16		0.025	0.010	7	T	649	1200	-	(2)	-	-	-
3415-16		0.025	0.010	8	T	649	1200	-	(2)	-	-	-
3415-16		0.025	0.010	9	T	871	1600	-	(2)	-	-	-
3415-16		0.025	0.010	10	T	871	1600	244.6	35.5	244.6	35.5	2.5
3415-16		0.025	0.010	11	T	982	1800	167.4	24.3	167.4	24.3	2.5
3415-16		0.025	0.010	12	T	982	1800	144.0	20.9	144.0	20.9	2.0
3415-16		0.025	0.010	129	L	982	1800	-	(2)	-	-	-
3415-16		0.025	0.010	130	L	982	1800	-	(2)	-	-	-
3415-16		0.025	0.010	114	45°	982	1800	137.1	19.9		19.6	2.0
3415-16		0.025	0.010	115	45°	982	1800	164.7	23.9	164.7	23.9	3.0
3415-16		0.025	0.010	13	T	1093	2000	-	(2)	-	-	-
3415-16		0.025	0.010	14	T	1093	2000	141.9	20.6	141.9	20.6	1.0
3415-16		0.025	0.010	110	T	1093	2000	128.8	18.7	128.8	18.7	3.0
3415-16		0.025	0.010	B	T	1093	2000	-	(2)	-	-	-
3415-16		0.025	0.010	E	T	1093	2000	121.3	17.6	121.3	17.6	2.0
3415-16		0.025	0.010	Q	T	1093	2000	118.5	17.2	118.5	17.2	5.5
3415-16		0.025	0.010	T	T	1093	2000	-	(2)	-	-	-
3415-17		0.025	0.010	B	T	1093	2000	130.2	18.9	130.2	18.9	3.0
3415-17		0.025	0.010	E	T	1093	2000	126.8	18.4	126.8	18.4	3.5
3415-17		0.025	0.010	Q	T	1093	2000	139.9	20.3	139.9	20.3	2.5
3415-17		0.025	0.010	T	T	1093	2000	109.6	15.9	109.6	15.9	2.5
3415-16		0.025	0.010	31	L	1093	2000	131.6	19.1	131.6	19.1	3.5
3415-16		0.025	0.010	32	L	1093	2000	126.8	18.4	126.8	18.4	2.0
3415-16		0.025	0.010	106	L	1093	2000	120.6	17.5	116.4	16.9	5.0
3415-16		0.025	0.010	113	L	1093	2000	122.6	17.8	122.6	17.8	2.0
3415-16		0.025	0.010	I	L	1093	2000	113.0	16.4	113.0	16.4	5.5

TABLE C-6

REPRODUCIBILITY TENSILE TEST DATA

Heat No.	Sheet No.	Gauge cm.	Gauge in.	Sample No.	Direction	Test Temp. °C	Test Temp. °F	UTS MN/m²	UTS ksi	YS MN/m²	YS ksi	Elong. %
3415-16		0.025	0.010	L	L	1093	2000	139.2	20.2	139.2	20.2	5.0
3415-16		0.025	0.010	O	L	1093	2000	117.8	17.1	117.8	17.1	4.5
3415-16		0.025	0.010	V	L	1093	2000	97.1	14.1	92.3	13.4	4.5
3415-16		0.025	0.010	Y	L	1093	2000	-	(2)	-	-	-
3415-16		0.025	0.010	BB	L	1093	2000	115.8	16.8	115.8	16.8	4.0
3415-17		0.025	0.010	I	L	1093	2000	-	(2)	-	-	-
3415-17		0.025	0.010	L	L	1093	2000	134.4	19.5	134.4	19.5	3.5
3415-17		0.025	0.010	O	L	1093	2000	130.9	19.0	126.1	18.3	2.5
3415-17		0.025	0.010	V	L	1093	2000	134.4	19.5	134.4	19.5	2.5
3415-17		0.025	0.010	Y	L	1093	2000	-	(2)	-	-	-
3415-17		0.025	0.010	BB	L	1093	2000	135.7	19.7	124.7	18.1	6.0
3415-16		0.025	0.010	37	45°	1093	2000	135.0	19.6	135.0	19.6	3.0
3415-16		0.025	0.010	38	45°	1093	2000	144.0	20.9	144.0	20.9	3.0
3415-16		0.025	0.010	15	T	1204	2200	86.8	12.6	86.8	12.6	1.0
3415-16		0.025	0.010	16	T	1204	2200	86.1	12.5	86.1	12.5	1.5
3415-16		0.025	0.010	131	L	1204	2200	70.3	10.2	70.3	10.2	0.5
3415-16		0.025	0.010	132	L	1204	2200	69.6	10.1	69.6	10.1	1.3
3415-16		0.025	0.010	116	45°	1204	2200	92.3	13.4	92.3	13.4	1.0
3415-16		0.025	0.010	117	45°	1204	2200	95.8	13.9	95.1	13.8	1.3
3415-16		0.025	0.010	141	T	1316	2400	50.3	7.3	32.4	4.7	3.0
3415-16		0.025	0.010	142	T	1316	2400	44.1	6.4	32.4	4.7	3.5

TABLE C-7

REPRODUCIBILITY TENSILE TEST DATA

Heat No.	Sheet No.	Gauge cm.	Gauge in.	Sample No.	Direction	Test Temp. °C	Test Temp. °F	UTS MN/m^2	UTS ksi	YS MN/m^2	YS ksi	Elong. %
3415-14		0.051	0.020	A	T	Room	Room	811.6	117.8	540.9	78.5	21.0
3415-14		0.051	0.020	D	T	Room	Room	828.2	120.2	551.4	80.9	20.5
3415-14		0.051	0.020	P	T	Room	Room	839.1	121.5	570.5	82.8	23.5
3415-14		0.051	0.020	S	T	Room	Room	824.7	119.7	556.1	80.7	22.5
3415-14		0.051	0.020	1	T	Room	Room	868.1	126.0	567.0	82.3	24.6
3415-14		0.051	0.020	2	T	Room	Room	881.9	128.0	576.0	83.6	24.6
3415-14		0.051	0.020	109	T	Room	Room	853.0	123.8	565.7	82.1	25.0
3415-13		0.051	0.020	A	T	Room	Room	770.3	111.8	513.3	74.5	25.0
3415-13		0.051	0.020	D	T	Room	Room	768.9	111.6	509.9	74.0	25.3
3415-13		0.051	0.020	P	T	Room	Room	792.4	115.0	529.8	76.9	24.9
3415-13		0.051	0.020	S	T	Room	Room	775.1	112.5	491.3	71.3	23.0
3415-14		0.051	0.020	H	L	Room	Room	891.6	129.4	635.9	92.3	15.0
3415-14		0.051	0.020	K	L	Room	Room	900.5	130.7	569.8	82.7	19.5
3415-14		0.051	0.020	N	L	Room	Room	911.5	132.3	598.1	86.8	18.5
3415-14		0.051	0.020	U	L	Room	Room	906.0	131.5	574.6	83.4	20.0
3415-14		0.051	0.020	X	L	Room	Room	886.7	128.7	575.3	83.5	16.5
3415-14		0.051	0.020	AA	L	Room	Room	873.7	126.8	608.4	88.3	20.0
3415-14		0.051	0.020	29	L	Room	Room	927.4	134.6	592.5	86.0	25.1
3415-14		0.051	0.020	30	L	Room	Room	931.5	135.2	585.7	85.0	17.5
3415-14		0.051	0.020	105	L	Room	Room	861.3	125.0	599.4	87.0	18.5
3415-14		0.051	0.020	112	L	Room	Room	934.3	135.6	604.3	87.7	16.5
3415-13		0.051	0.020	H	L	Room	Room	822.0	119.3	547.8	79.5	15.0
3415-13		0.051	0.020	K	L	Room	Room	861.8	125.0	532.6	77.3	17.3
3415-13		0.051	0.020	N	L	Room	Room	839.2	121.8	553.3	80.3	15.2
3415-13		0.051	0.020	U	L	Room	Room	767.5	111.4	529.2	76.8	12.5
3415-13		0.051	0.020	X	L	Room	Room	765.5	111.1	508.8	73.8	14.2
3415-13		0.051	0.020	AA	L	Room	Room	830.2	120.5	538.1	78.1	17.2
3415-14		0.051	0.020	35	45°	Room	Room	870.2	126.3	578.1	83.9	24.9
3415-14		0.051	0.020	36	45°	Room	Room	888.8	129.0	591.2	85.8	25.0

TABLE C-8

REPRODUCIBILITY TENSILE TEST DATA

Heat No.	Sheet No.	Gauge cm.	Gauge in.	Sample No.	Direction	Test Temp. °C	Test Temp. °F	UTS MN/m^2	UTS ksi	YS MN/m^2	YS ksi	Elong. %
3415-14		0.051	0.020	3	T	204	400	758.6	110.1	508.5	73.8	20.0
3415-14		0.051	0.020	4	T	204	400	760.0	110.3	489.2	71.0	21.0
3415-14		0.051	0.020	5	T	427	800	620.1	90.0	(2)		
3415-14		0.051	0.020	6	T	427	800	613.2	89.0	416.8	60.5	21.5
3415-14		0.051	0.020	7	T	649	1200	387.9	56.3	330.0	47.9	6.0
3415-14		0.051	0.020	8	T	649	1200	387.2	56.2	324.5	47.1	7.5
3415-14		0.051	0.020	9	T	871	1600	229.4	33.3	227.4	33.0	3.6
3415-14		0.051	0.020	10	T	871	1600	215.0	31.2	215.0	31.2	2.5
3415-14		0.051	0.020	11	T	982	1800	163.3	23.7	162.6	23.6	2.5
3415-14		0.051	0.020	12	T	982	1800	170.2	24.7	170.2	24.7	2.5
3415-14		0.051	0.020	129	L	982	1800	167.4	24.3	159.8	23.2	3.0
3415-14		0.051	0.020	130	L	982	1800	178.5	25.9	175.7	25.5	3.0
3415-14		0.051	0.020	114	45°	982	1800	169.5	24.6	168.1	24.4	5.0
3415-14		0.051	0.020	115	45°	982	1800	172.3	25.0	170.9	24.8	4.5
3415-14		0.051	0.020	13	T	1093	2000	139.9	20.3	139.9	20.3	2.0
3415-14		0.051	0.020	14	T	1093	2000	127.5	18.5	127.5	18.5	2.0
3415-14		0.051	0.020	110	T	1093	2000	143.3	20.8	143.3	20.8	2.0
3415-14		0.051	0.020	B	T	1093	2000	126.8	18.4	126.8	18.4	2.0
3415-14		0.051	0.020	E	T	1093	2000	130.2	18.9	130.2	18.9	2.1
3415-14		0.051	0.020	Q	T	1093	2000	135.7	19.7	135.7	19.7	2.0
3415-14		0.051	0.020	T	T	1093	2000	136.4	19.8	130.9	19.0	2.0
3415-13		0.051	0.020	B	T	1093	2000	124.0	18.0	124.0	18.0	2.5
3415-13		0.051	0.020	E	T	1093	2000	124.0	18.0	124.0	18.0	2.4
3415-13		0.051	0.020	Q	T	1093	2000	119.2	17.3	119.2	17.3	2.0
3415-13		0.051	0.020	T	T	1093	2000	116.4	16.9	116.4	16.9	1.2
3415-14		0.051	0.020	31	L	1093	2000	147.4	21.4	146.7	21.3	4.0
3415-14		0.051	0.020	32	L	1093	2000	138.5	20.1	136.4	19.8	2.5
3415-14		0.051	0.020	106	L	1093	2000	146.8	21.3	146.1	21.2	3.5
3415-14		0.051	0.020	113	L	1093	2000	150.2	21.8	149.5	21.7	3.0

TABLE C-9

REPRODUCIBILITY TENSILE TEST DATA

Heat No.	Sheet No.	Gauge cm.	Gauge in.	Sample No.	Direction	Test Temp. °C	Test Temp. °F	UTS MN/m^2	UTS ksi	YS MN/m^2	YS ksi	Elong. %
3415-14		0.051	0.020	I	L	1093	2000	139.2	20.2	135.0	19.6	2.4
3415-14		0.051	0.020	L	L	1093	2000	145.4	21.1	139.9	20.3	3.2
3415-14		0.051	0.020	O	L	1093	2000	143.3	20.8	132.3	19.2	3.0
3415-14		0.051	0.020	V	L	1093	2000	132.3	19.2	128.8	18.7	2.5
3415-14		0.051	0.020	Y	L	1093	2000	133.7	19.4	132.3	19.2	2.5
3415-14		0.051	0.020	BB	L	1093	2000	145.4	21.1	140.6	20.4	2.5
3415-13		0.051	0.020	I	L	1093	2000	129.5	18.8	129.5	18.8	1.8
3415-13		0.051	0.020	L	L	1093	2000	120.6	17.5	104.7	15.2	2.5
3415-13		0.051	0.020	O	L	1093	2000	126.8	18.4	126.8	18.4	1.9
3415-13		0.051	0.020	V	L	1093	2000	126.1	18.3	122.0	17.7	3.0
3415-13		0.051	0.020	Y	L	1093	2000	108.9	15.8	108.9	15.8	1.4
3415-13		0.051	0.020	BB	L	1093	2000	126.1	18.3	126.1	18.3	1.7
3415-14		0.051	0.020	37	45°	1093	2000	148.1	21.5	148.1	21.5	2.5
3415-14		0.051	0.020	38	45°	1093	2000	145.4	21.1	145.4	21.1	3.5
3415-14		0.051	0.020	15	T	1204	2200	83.4	12.1	83.4	12.1	1.1
3415-14		0.051	0.020	16	T	1204	2200	95.1	13.8	95.1	13.8	1.0
3415-14		0.051	0.020	131	L	1204	2200	104.7	15.2	104.7	15.2	1.8
3415-14		0.051	0.020	132	L	1204	2200	102.7	14.9	102.7	14.4	1.0
3415-14		0.051	0.020	116	45°	1204	2200	96.5	14.0	96.5	14.0	1.6
3415-14		0.051	0.020	117	45°	1204	2200	90.3	13.1	90.3	13.1	2.0
3415-14		0.051	0.020	141	T	1316	2400	44.1	6.4	40.0	5.8	2.0
3415-14		0.051	0.020	142	T	1316	2400	36.5	5.3	32.4	4.7	2.0

TABLE C-10

REPRODUCIBILITY TENSILE TEST DATA

Heat No.	Sheet No.	Gauge cm.	Gauge in.	Sample No.	Direction	Test Temp. °C	Test Temp. °F	UTS MN/m^2	UTS ksi	YS MN/m^2	YS ksi	Elong. %
3456-10		0.076	0.030	A	T	Room	Room	822.0	119.3	534.7	77.6	21.7
3456-10		0.076	0.030	D	T	Room	Room	841.3	122.1	544.3	79.0	21.2
3456-10		0.076	0.030	P	T	Room	Room	808.2	117.3	516.8	75.0	24.4
3456-10		0.076	0.030	S	T	Room	Room	832.3	120.8	535.4	77.7	22.0
3456-10		0.076	0.030	1	T	Room	Room	826.1	119.9	555.3	80.6	16.9
3456-10		0.076	0.030	2	T	Room	Room	842.6	122.3	566.4	82.2	21.3
3456-10		0.076	0.030	109	T	Room	Room	888.8	129.0	576.0	83.6	20.0
3456-9		0.076	0.030	A	T	Room	Room	788.2	114.4	510.5	74.1	22.9
3456-9		0.076	0.030	D	T	Room	Room	805.4	116.9	512.6	74.4	25.3
3456-9		0.076	0.030	P	T	Room	Room	815.8	118.4	529.2	76.8	19.5
3456-9		0.076	0.030	S	T	Room	Room	845.4	122.7	553.3	80.3	23.0
3456-10		0.076	0.030	H	L	Room	Room	909.5	132.0	571.2	82.9	19.5
3456-10		0.076	0.030	K	L	Room	Room	921.2	133.7	576.0	83.6	21.7
3456-10		0.076	0.030	N	L	Room	Room	908.1	131.8	569.8	82.7	18.8
3456-10		0.076	0.030	U	L	Room	Room	918.4	133.3	573.9	83.3	20.4
3456-10		0.076	0.030	X	L	Room	Room	909.5	132.0	562.9	81.7	18.0
3456-10		0.076	0.030	AA	L	Room	Room	885.4	128.5	548.4	79.6	16.0
3456-10		0.076	0.030	29	L	Room	Room	884.7	128.4	574.6	83.4	20.0
3456-10		0.076	0.030	30	L	Room	Room	924.6	134.2	595.3	86.4	15.0
3456-10		0.076	0.030	105	L	Room	Room	944.6	137.1	607.0	88.1	20.0
3456-10		0.076	0.030	112	L	Room	Room	922.6	133.9	604.9	87.8	17.5
3456-9		0.076	0.030	H	L	Room	Room	883.3	128.2	596.0	86.5	20.0
3456-9		0.076	0.030	K	L	Room	Room	890.9	129.3	558.8	81.1	(1)
3456-9		0.076	0.030	N	L	Room	Room	880.5	127.8	558.1	81.0	(1)
3456-9		0.076	0.030	U	L	Room	Room	893.6	129.7	566.4	82.2	(1)
3456-9		0.076	0.030	X	L	Room	Room	910.9	132.2	558.1	81.0	(1)
3456-9		0.076	0.030	AA	L	Room	Room	900.5	130.7	567.0	82.3	17.5
3456-10		0.076	0.030	35	45°	Room	Room	854.4	124.0	578.1	83.9	22.5
3456-10		0.076	0.030	36	45°	Room	Room	854.4	124.0	607.0	88.1	20.0

TABLE C-11

REPRODUCIBILITY TENSILE TEST DATA

Heat No.	Sheet No.	Gauge cm.	Gauge in.	Sample No.	Direction	Test Temp. °C	Test Temp. °F	UTS MN/m²	UTS ksi	YS MN/m²	YS ksi	Elong. %
3456-10		0.076	0.030	3	T	204	400	760.7	110.4	510.5	74.1	22.5
3456-10		0.076	0.030	4	T	204	400	754.5	109.5	505.7	73.4	20.0
3456-10		0.076	0.030	5	T	427	800	691.8	100.4	458.2	66.5	21.5
3456-10		0.076	0.030	6	T	427	800	726.9	105.5	478.2	69.4	20.0
3456-10		0.076	0.030	7	T	649	1200	401.7	58.3	334.9	48.6	9.0
3456-10		0.076	0.030	8	T	649	1200	375.5	54.5	323.1	46.9	7.5
3456-10		0.076	0.030	9	T	871	1600	220.5	32.0	217.0	31.5	5.0
3456-10		0.076	0.030	10	T	871	1600	226.7	32.9	224.6	32.6	4.6
3456-10		0.076	0.030	11	T	982	1800	175.7	25.5	175.7	25.5	2.0
3456-10		0.076	0.030	12	T	982	1800	172.3	25.0	170.2	24.7	2.5
3456-10		0.076	0.030	129	L	982	1800	172.3	25.0	161.9	23.5	5.0
3456-10		0.076	0.030	130	L	982	1800	174.3	25.3	164.7	23.9	4.5
3456-10		0.076	0.030	114	45°	982	1800	187.4	27.2	182.6	26.5	2.5
3456-10		0.076	0.030	115	45°	982	1800	170.2	24.7	168.1	24.4	4.5
3456-10		0.076	0.030	13	T	1093	2000	152.3	22.1	152.3	22.1	1.6
3456-10		0.076	0.030	14	T	1093	2000	144.7	21.0	144.7	21.0	1.0
3456-10		0.076	0.030	110	T	1093	2000	149.5	21.7	148.8	21.6	2.3
3456-10		0.076	0.030	B	T	1093	2000	118.5	17.2	118.5	17.2	2.0
3456-10		0.076	0.030	E	T	1093	2000	133.7	19.4	-	-	2.5
3456-10		0.076	0.030	Q	T	1093	2000	127.5	18.5	127.5	18.5	2.0
3456-10		0.076	0.030	T	T	1093	2000	136.4	19.8	136.4	19.8	2.5
3456-9		0.076	0.030	B	T	1093	2000	122.6	17.8	122.6	17.8	2.0
3456-9		0.076	0.030	E	T	1093	2000	135.7	19.7	135.7	19.7	2.5
3456-9		0.076	0.030	Q	T	1093	2000	128.8	18.7	128.8	18.7	2.0
3456-9		0.076	0.030	T	T	1093	2000	122.6	17.8	122.6	17.8	2.5
3456-10		0.076	0.030	31	L	1093	2000	155.7	22.6	153.0	22.2	3.1
3456-10		0.076	0.030	32	L	1093	2000	156.4	22.7	152.3	22.1	3.0
3456-10		0.076	0.030	106	L	1093	2000	156.4	22.7	155.7	22.6	2.0
3456-10		0.076	0.030	113	L	1093	2000	157.1	22.8	151.6	22.0	3.5

TABLE C-12

REPRODUCIBILITY TENSILE TEST DATA

Heat No.	Sheet No.	Gauge cm.	Gauge in.	Sample No.	Direction	Test Temp. °C	Test Temp. °F	UTS MN/m^2	UTS ksi	YS MN/m^2	YS ksi	Elong. %
3456-10		0.076	0.030	I	L	1093	2000	141.9	20.6	140.6	20.4	3.0
3456-10		0.076	0.030	L	L	1093	2000	139.2	20.2	138.5	20.1	2.5
3456-10		0.076	0.030	O	L	1093	2000	142.6	20.7	141.9	20.6	3.0
3456-10		0.076	0.030	V	L	1093	2000	135.0	19.6	135.0	19.6	2.5
3456-10		0.076	0.030	Y	L	1093	2000	139.9	20.3	138.5	20.1	2.9
3456-10		0.076	0.030	BB	L	1093	2000	146.8	21.3	146.1	21.2	3.0
3456-9		0.076	0.030	I	L	1093	2000	143.3	20.8	141.2	20.5	2.5
3456-9		0.076	0.030	L	L	1093	2000	146.1	21.2	144.0	20.9	3.8
3456-9		0.076	0.030	O	L	1093	2000	141.2	20.5	141.2	20.5	2.5
3456-9		0.076	0.030	V	L	1093	2000	141.2	20.5	133.7	19.4	3.0
3456-9		0.076	0.030	Y	L	1093	2000	143.3	20.8	141.9	20.6	2.5
3456-9		0.076	0.030	BB	L	1093	2000	139.2	20.2	134.4	19.5	2.5
3456-10		0.076	0.030	37	45°	1093	2000	153.6	22.3	150.9	21.9	2.0
3456-10		0.076	0.030	38	45°	1093	2000	153.0	22.2	153.0	22.2	1.4
3456-10		0.076	0.030	15	T	1204	2200	83.4	12.1	83.4	12.1	2.5
3456-10		0.076	0.030	16	T	1204	2200	108.9	15.8	108.9	15.8	4.0
3456-10		0.076	0.030	131	L	1204	2200	117.8	17.1	117.8	17.1	4.0
3456-10		0.076	0.030	132	L	1204	2200	120.6	17.5	119.2	17.3	3.5
3456-10		0.076	0.030	116	45°	1204	2200	107.5	15.6	107.5	15.6	4.0
3456-10		0.076	0.030	117	45°	1204	2200	112.3	16.3	112.3	16.3	4.5
3456-10		0.076	0.030	141	T	1316	2400	56.5	8.2	54.4	7.9	3.0
3456-10		0.076	0.030	142	T	1316	2400	48.2	7.0	35.1	5.1	2.0

TABLE C-13

REPRODUCIBILITY TENSILE TEST DATA

Heat No.	Sheet No.	Gauge cm.	Gauge in.	Sample No.	Direction	Test Temp. °C	Test Temp. °F	UTS MN/m²	UTS ksi	YS MN/m²	YS ksi	Elong. %
3502-20		0.025	0.010	A	T	Room	Room	826.8	120.0	584.3	84.8	17.5
3502-20		0.025	0.010	D	T	Room	Room	782.0	113.5	560.2	81.3	16.0
3502-20		0.025	0.010	P	T	Room	Room	793.7	115.2	566.4	82.2	12.5
3502-20		0.025	0.010	S	T	Room	Room	824.0	119.6	577.4	83.8	20.0
3502-20		0.025	0.010	1	T	Room	Room	834.4	121.1	598.1	86.8	18.8
3502-20		0.025	0.010	2	T	Room	Room	817.2	118.6	560.8	81.4	20.0
3502-20		0.025	0.010	109	T	Room	Room	850.2	123.4	626.3	90.9	18.5
3502-24		0.025	0.010	A	T	Room	Room	911.5	132.3	640.8	93.0	25.0
3502-24		0.025	0.010	D	T	Room	Room	894.3	129.8	609.1	88.4	17.0
3502-24		0.025	0.010	P	T	Room	Room	921.9	133.8	636.6	92.4	24.0
3502-24		0.025	0.010	S	T	Room	Room	-	(2)	-	-	-
3502-20		0.025	0.010	H	L	Room	Room	847.5	123.0	609.1	88.4	12.5
3502-20		0.025	0.010	K	L	Room	Room	893.6	129.7	609.1	88.4	15.0
3502-20		0.025	0.010	N	L	Room	Room	893.6	129.7	599.4	87.0	16.0
3502-20		0.025	0.010	U	L	Room	Room	868.8	126.1	607.7	88.2	13.0
3502-20		0.025	0.010	X	L	Room	Room	857.1	124.4	598.1	86.8	15.0
3502-20		0.025	0.010	AA	L	Room	Room	851.6	123.6	604.9	87.8	12.5
3502-20		0.025	0.010	29	L	Room	Room	900.5	130.7	612.5	88.9	17.0
3502-20		0.025	0.010	30	L	Room	Room	788.2	114.4	617.3	89.6	6.5
3502-20		0.025	0.010	105	L	Room	Room	883.3	128.2	661.4	96.0	9.5
3502-20		0.025	0.010	112	L	Room	Room	879.2	127.6	617.3	89.6	12.5
3502-24		0.025	0.010	H	L	Room	Room	992.2	144.0	633.2	91.9	9.0
3502-24		0.025	0.010	K	L	Room	Room	895.0	129.9	605.6	87.9	10.0
3502-24		0.025	0.010	N	L	Room	Room	922.6	133.9	613.9	89.1	15.0
3502-24		0.025	0.010	U	L	Room	Room	948.8	137.7	641.5	93.1	15.0
3502-24		0.025	0.010	X	L	Room	Room	977.7	141.9	671.1	97.4	15.0
3502-24		0.025	0.010	AA	L	Room	Room	1033.5	150.0	695.9	101.0	16.0
3502-20		0.025	0.010	35	45	Room	Room	817.2	178.6	584.3	84.8	12.0
3502-20		0.025	0.010	36	45	Room	Room	771.7	112.0	606.3	88.0	9.5
3502-20		0.025	0.010	3	T	204	400	-	(2)	-	-	-

TABLE C-14

REPRODUCIBILITY TENSILE TEST DATA

Heat No.	Sheet No.	Gauge cm.	Gauge in.	Sample No.	Direction	Test Temp. °C	Test Temp. °F	UTS MN/m²	UTS ksi	YS MN/m²	YS ksi	Elong. %
3502-20		0.025	0.010	4	T	204	400	757.9	110.0	528.5	76.7	15.0
3502-20		0.025	0.010	5	T	427	800	607.7	88.2	469.9	68.2	19.0
3502-20		0.025	0.010	6	T	427	800	628.4	91.2	463.7	67.3	19.0
3502-20		0.025	0.010	7	T	649	1200	-	(2)	-	-	-
3502-20		0.025	0.010	8	T	649	1200	378.3	54.9	368.6	53.5	3.5
3502-20		0.025	0.010	9	T	871	1600	233.6	33.9	233.6	33.9	2.0
3502-20		0.025	0.010	10	T	871	1600	226.7	32.9	226.7	32.9	2.0
3502-20		0.025	0.010	11	T	982	1800	148.8	21.6	148.8	21.6	2.0
3502-20		0.025	0.010	12	T	982	1800	150.2	21.8	150.2	21.8	2.5
3502-20		0.025	0.010	129	L	982	1800	181.2	26.3	180.5	26.2	5.0
3502-20		0.025	0.010	130	L	982	1800	-	(2)	-	-	-
3502-20		0.025	0.010	114	45°	982	1800	151.6	22.0	150.9	21.9	2.5
3502-20		0.025	0.010	115	45°	982	1800	147.4	21.4	147.4	21.4	2.0
3502-20		0.025	0.010	13	T	1093	2000	130.9	19.0	130.9	19.0	2.5
3502-20		0.025	0.010	14	T	1093	2000	137.8	20.0	137.8	20.0	2.0
3502-20		0.025	0.010	110	T	1093	2000	130.2	18.9	130.2	18.9	2.0
3502-20		0.025	0.010	B	T	1093	2000	138.5	20.1	138.5	20.1	2.0
3502-20		0.025	0.010	E	T	1093	2000	124.7	18.1	124.7	18.1	2.5
3502-20		0.025	0.010	Q	T	1093	2000	115.1	16.7	115.1	16.7	2.0
3502-20		0.025	0.010	T	T	1093	2000	104.0	15.1	104.0	15.1	5.0
3502-24		0.025	0.010	B	T	1093	2000	121.3	17.6	121.3	17.6	4.0
3502-24		0.025	0.010	E	T	1093	2000	104.0	15.1	104.0	15.1	2.0
3502-24		0.025	0.010	Q	T	1093	2000	123.3	17.9	123.3	17.9	2.5
3502-24		0.025	0.010	T	T	1093	2000	122.6	17.8	122.6	17.8	2.5
3502-20		0.025	0.010	31	L	1093	2000	129.5	18.8	129.5	18.8	1.0
3502-20		0.025	0.010	32	L	1093	2000	140.6	20.4	140.6	20.4	2.5
3502-20		0.025	0.010	106	L	1093	2000	140.6	20.4	140.6	20.4	2.4
3502-20		0.025	0.010	113	L	1093	2000	132.3	19.2	132.3	19.2	2.5
3502-20		0.025	0.010	I	L	1093	2000	-	(2)	-	-	-
3502-20		0.025	0.010	L	L	1093	2000	122.0	17.7	122.0	17.7	3.5

TABLE C-15

REPRODUCIBILITY TENSILE TEST DATA

Heat No.	Sheet No.	Gauge cm.	Gauge in.	Sample No.	Direction	Test Temp. °C	Test Temp. °F	UTS MN/m²	UTS ksi	YS MN/m²	YS ksi	Elong. %
3502-20		0.025	0.010	O	L	1093	2000	133.7	19.4	133.7	19.4	2.5
3502-20		0.025	0.010	V	L	1093	2000	128.8	18.7	128.8	18.7	3.5
3502-20		0.025	0.010	Y	L	1093	2000	134.4	19.5	134.4	19.5	3.0
3502-20		0.025	0.010	BB	L	1093	2000	-	(2)	-	-	-
3502-24		0.025	0.010	I	L	1093	2000	126.1	18.3	126.1	18.3	2.0
3502-24		0.025	0.010	L	L	1093	2000	125.4	18.2	121.3	17.6	3.5
3502-24		0.025	0.010	O	L	1093	2000	-	(2)	-	-	-
3502-24		0.025	0.010	V	L	1093	2000	-	(2)	-	-	-
3502-24		0.025	0.010	Y	L	1093	2000	120.6	17.5	120.6	17.5	4.0
3502-24		0.025	0.010	BB	L	1093	2000	-	(2)	-	(2)	-
3502-20		0.025	0.010	37	45°	1093	2000	155.7	22.6	155.7	22.6	2.0
3502-20		0.025	0.010	38	45°	1093	2000	155.7	22.6	155.7	22.6	2.5
3502-20		0.025	0.010	15	T	1204	2200	89.6	13.0	89.6	13.0	2.5
3502-20		0.025	0.010	16	T	1204	2200	88.2	12.8	88.2	12.8	2.5
3502-20		0.025	0.010	131	L	1204	2200	90.3	13.1	90.3	13.1	2.0
3502-20		0.025	0.010	132	L	1204	2200	78.5	11.4	78.5	11.4	2.5
3502-20		0.025	0.010	116	45°	1204	2200	87.5	12.7	87.5	12.7	1.5
3502-20		0.025	0.010	117	45°	1204	2200	92.3	13.4	92.3	13.4	3.0
3502-20		0.025	0.010	141	T	1316	2400	37.9	5.5	37.9	5.5	3.0
3502-20		0.025	0.010	142	T	1316	2400	37.9	5.5	37.9	5.5	5.0

TABLE C-16

REPRODUCIBILITY TENSILE TEST DATA

Heat No.	Sheet No.	Gauge cm.	Gauge in.	Sample No.	Direction	Test Temp. °C	Test Temp. °F	UTS MN/m²	UTS ksi	YS MN/m²	YS ksi	Elong. %
3502-1		0.051	0.020	A	T	Room	Room	766.9	111.3	518.1	75.2	23.2
3502-1		0.051	0.020	D	T	Room	Room	795.1	115.4	538.8	78.2	23.3
3502-1		0.051	0.020	P	T	Room	Room	195.8	115.5	550.5	79.9	20.5
3502-1		0.051	0.020	S	T	Room	Room	782.0	113.5	523.6	76.0	20.3
3502-1		0.051	0.020	1	T	Room	Room	825.4	119.8	569.8	82.7	20.0
3502-1		0.051	0.020	2	T	Room	Room	826.8	120.0	547.1	79.4	23.0
3502-1		0.051	0.020	109	T	Room	Room	847.5	123.0	571.9	83.0	22.5
3502-2		0.051	0.020	A	T	Room	Room	884.7	128.4	580.8	84.3	22.0
3502-2		0.051	0.020	D	T	Room	Room	889.5	129.1	611.8	88.8	21.5
3502-2		0.051	0.020	P	T	Room	Room	842.0	122.2	577.4	83.8	21.0
3502-2		0.051	0.020	S	T	Room	Room	873.0	126.7	557.4	80.9	21.0
3502-1		0.051	0.020	H	L	Room	Room	867.5	125.9	563.6	81.8	18.6
3502-1		0.051	0.020	K	L	Room	Room	869.5	126.2	567.7	82.4	16.9
3502-1		0.051	0.020	N	L	Room	Room	827.5	120.1	561.5	81.5	16.0
3502-1		0.051	0.020	U	L	Room	Room	856.4	124.3	582.2	84.5	16.2
3502-1		0.051	0.020	X	L	Room	Room	862.6	125.2	573.2	83.2	16.0
3502-1		0.051	0.020	AA	L	Room	Room	868.1	126.0	571.9	83.0	16.0
3502-1		0.051	0.020	29	L	Room	Room	905.3	131.4	586.3	85.1	20.0
3502-1		0.051	0.020	30	L	Room	Room	877.5	120.1	876.0	83.6	13.0
3502-1		0.051	0.020	105	L	Room	Room	857.8	124.5	602.9	87.5	10.0
3502-1		0.051	0.020	112	L	Room	Room	895.7	130.0	595.3	86.4	13.0
3502-2		0.051	0.020	H	L	Room	Room	840.5	136.5	629.7	91.4	16.0
3502-2		0.051	0.020	K	L	Room	Room	991.5	143.9	664.9	96.5	17.0
3502-2		0.051	0.020	N	L	Room	Room	1016.3	147.5	670.4	97.3	15.0
3502-2		0.051	0.020	U	L	Room	Room	928.1	134.7	677.3	98.3	20.0
3502-2		0.051	0.020	X	L	Room	Room	969.4	140.7	655.9	95.2	20.0
3502-2		0.051	0.020	AA	L	Room	Room	973.6	141.3	650.4	94.4	21.0
3502-1		0.051	0.020	35	45°	Room	Room	824.0	119.6	565.0	82.0	15.0
3502-1		0.051	0.020	36	45°	Room	Room	835.8	121.3	565.7	82.1	15.0
3502-1		0.051	0.020	3	T	204	400	776.5	112.7	504.3	73.2	19.5

TABLE C-17

REPRODUCIBILITY TENSILE TEST DATA

Heat No.	Sheet No.	Gauge cm.	Gauge in.	Sample No.	Direction	Test Temp. °C	Test Temp. °F	UTS MN/m²	UTS ksi	YS MN/m²	YS ksi	Elong. %
3502-1		0.051	0.020	4	T	204	400	780.6	113.3	507.1	73.6	20.0
3502-1		0.051	0.020	5	T	427	800	636.6	92.4	445.8	64.7	21.5
3502-1		0.051	0.020	6	T	427	800	662.1	96.1	447.9	65.0	22.0
3502-1		0.051	0.020	7	T	649	1200	444.4	64.5	349.3	50.7	9.5
3502-1		0.051	0.020	8	T	649	1200	414.8	60.2	331.4	48.1	6.5
3502-1		0.051	0.020	9	T	871	1600	232.2	33.7	232.2	33.7	2.5
3502-1		0.051	0.020	10	T	871	1600	247.4	35.9	243.2	35.3	3.0
3502-1		0.051	0.020	11	T	982	1800	176.4	25.6	172.3	25.0	3.5
3502-1		0.051	0.020	12	T	982	1800	160.5	23.3	160.5	23.3	4.0
3502-1		0.051	0.020	129	L	982	1800	175.0	25.4	171.6	24.9	5.5
3502-1		0.051	0.020	130	L	982	1800	179.1	26.0	177.1	25.7	7.0
3502-1		0.051	0.020	114	45°	982	1800	184.7	26.8	177.1	25.7	5.0
3502-1		0.051	0.020	115	45°	982	1800	171.6	24.9	169.5	24.6	4.5
3502-1		0.051	0.020	13	T	1093	2000	141.2	20.5	141.2	20.5	5.0
3502-1		0.051	0.020	14	T	1093	2000	137.8	20.0	137.8	20.0	4.5
3502-1		0.051	0.020	110	T	1093	2000	136.4	19.8	136.4	19.8	4.5
3502-1		0.051	0.020	B	T	1093	2000	126.1	18.3	126.1	18.3	2.9
3502-1		0.051	0.020	E	T	1093	2000	138.5	20.1	138.5	20.1	2.3
3502-1		0.051	0.020	Q	T	1093	2000	137.8	20.0	137.8	20.0	2.4
3502-1		0.051	0.020	T	T	1093	2000	136.4	19.8	136.4	19.8	2.5
3502-2		0.051	0.020	B	T	1093	2000	132.3	19.2	132.3	19.2	1.7
3502-2		0.051	0.020	E	T	1093	2000	120.6	17.5	120.6	17.5	1.0
3502-2		0.051	0.020	Q	T	1093	2000	119.9	17.4		(2)	-
3502-2		0.051	0.020	T	T	1093	2000	130.2	18.9	130.2	18.9	1.5
3502-1		0.051	0.020	31	L	1093	2000	128.8	18.7	128.8	18.7	4.5
3502-1		0.051	0.020	32	L	1093	2000	144.7	21.0	143.3	20.8	5.0
3502-1		0.051	0.020	106	L	1093	2000	133.7	19.4	133.7	19.4	4.5
3502-1		0.051	0.020	113	L	1093	2000	133.0	19.3	133.0	19.3	4.0
3502-1		0.051	0.020	I	L	1093	2000	137.8	20.0	130.9	19.0	3.7

TABLE C-18

REPRODUCIBILITY TENSILE TEST DATA

Heat No.	Sheet No.	Gauge cm.	Gauge in.	Sample No.	Direction	Test Temp. °C	Test Temp. °F	UTS MN/m²	UTS ksi	YS MN/m²	YS ksi	Elong. %
3502-1		0.051	0.020	L	L	1093	2000	140.6	20.4	140.6	20.4	3.5
3502-1		0.051	0.020	O	L	1093	2000	144.0	20.9	139.8	20.3	2.5
3502-1		0.051	0.020	V	L	1093	2000	146.1	21.2	143.3	20.8	3.0
3502-1		0.051	0.020	Y	L	1093	2000	143.3	20.8	132.9	19.3	2.4
3502-1		0.051	0.020	BB	L	1093	2000	137.8	20.0	137.8	20.0	2.4
3502-2		0.051	0.020	I	L	1093	2000	110.9	16.1	107.5	15.6	1.0
3502-2		0.051	0.020	L	L	1093	2000	140.5	20.4	140.5	20.4	1.5
3502-2		0.051	0.020	O	L	1093	2000	119.2	17.3		(2)	-
3502-2		0.051	0.020	V	L	1093	2000	145.4	21.1	144.0	20.9	2.5
3502-2		0.051	0.020	Y	L	1093	2000	141.9	20.6	137.1	19.9	2.4
3502-2		0.051	0.020	BB	L	1093	2000	137.8	20.0	137.1	19.9	2.5
3502-1		0.051	0.020	37	45°	1093	2000	141.2	20.5	141.2	20.5	5.5
3502-1		0.051	0.020	38	45°	1093	2000	140.5	20.4	140.5	20.4	5.5
3502-1		0.051	0.020	15	T	1204	2200	90.9	13.2	90.9	13.2	2.5
3502-1		0.051	0.020	16	T	1204	2200	88.9	12.9	88.9	12.9	2.4
3502-1		0.051	0.020	131	L	1204	2200		(2)		-	-
3502-1		0.051	0.020	132	L	1204	2200	95.8	13.9	95.8	13.9	1.8
3502-1		0.051	0.020	116	45°	1204	2200	86.1	12.5	86.1	12.5	1.5
3502-1		0.051	0.020	117	45°	1204	2200	96.5	14.0	96.5	14.0	3.0
3502-1		0.051	0.020	141	T	1316	2400	52.4	7.6	51.0	7.4	1.0
3502-1		0.051	0.020	142	T	1316	2400					

TABLE C-19

REPRODUCIBILITY TENSILE TEST DATA

Heat No.	Sheet No.	Gauge cm.	Gauge in.	Sample No.	Direction	Test Temp. °C	Test Temp. °F	UTS MN/m^2	UTS ksi	YS MN/m^2	YS ksi	Elong. %
3502-5		0.076	0.030	A	T	Room	Room	857.8	124.5	565.0	82.0	21.1
3502-5		0.076	0.030	D	T	Room	Room	864.7	125.5	583.6	84.7	20.5
3502-5		0.076	0.030	P	T	Room	Room	866.1	125.7	572.6	83.1	20.0
3502-5		0.076	0.030	S	T	Room	Room	865.4	125.6	558.1	81.0	22.4
3502-5		0.076	0.030	1	T	Room	Room	861.9	125.1	585.7	85.0	20.0
3502-5		0.076	0.030	2	T	Room	Room	875.0	127.0	577.4	83.8	23.0
3502-5		0.076	0.030	109	T	Room	Room	886.7	128.7	588.4	85.4	22.0
3502-4		0.076	0.030	A	T	Room	Room	870.9	126.4	564.3	81.9	23.2
3502-4		0.076	0.030	D	T	Room	Room	866.8	125.8	553.3	80.3	22.3
3502-4		0.076	0.030	P	T	Room	Room	842.0	122.2	546.4	79.3	24.2
3502-4		0.076	0.030	S	T	Room	Room	853.7	123.9	548.4	79.6	20.0
3502-5		0.076	0.030	H	L	Room	Room	926.0	134.4	587.8	85.3	19.4
3502-5		0.076	0.030	K	L	Room	Room	934.3	135.6	591.2	85.8	15.0
3502-5		0.076	0.030	N	L	Room	Room	927.4	134.6	593.3	86.1	(1)
3502-5		0.076	0.030	U	L	Room	Room	905.3	131.4	567.0	82.3	17.5
3502-5		0.076	0.030	X	L	Room	Room	917.1	133.1	590.5	85.7	(1)
3502-5		0.076	0.030	AA	L	Room	Room	912.9	132.5	579.4	84.1	18.0
3502-5		0.076	0.030	29	L	Room	Room	919.1	133.4	613.9	89.1	20.0
3502-5		0.076	0.030	30	L	Room	Room	909.5	132.0	592.5	86.0	15.0
3502-5		0.076	0.030	105	L	Room	Room	936.4	135.9	607.7	88.2	15.0
3502-5		0.076	0.030	112	L	Room	Room	906.0	131.5	597.4	86.7	13.0
3502-4		0.076	0.030	H	L	Room	Room	870.2	126.3	565.0	82.0	(1)
3502-4		0.076	0.030	K	L	Room	Room	897.8	130.3	567.7	82.4	(1)
3502-4		0.076	0.030	N	L	Room	Room	910.9	132.2	582.9	84.6	(1)
3502-4		0.076	0.030	U	L	Room	Room	902.6	131.0	576.0	83.6	(1)
3502-4		0.076	0.030	X	L	Room	Room	897.8	130.3	571.2	82.9	17.0
3502-4		0.076	0.030	AA	L	Room	Room	919.8	133.5	571.9	83.0	16.3
3502-5		0.076	0.030	35	45°	Room	Room	843.3	122.4	591.2	85.8	18.0
3502-5		0.076	0.030	36	45°	Room	Room	858.5	124.6	594.6	86.3	23.0

TABLE C-20

REPRODUCIBILITY TENSILE TEST DATA

Heat No.	Sheet No.	Gauge cm.	Gauge in.	Sample No.	Direction	Test Temp. °C	Test Temp. °F	UTS MN/m^2	UTS ksi	YS MN/m^2	YS ksi	Elong. %
3502-5		0.076	0.030	3	T	204	400	815.8	118.4	542.9	78.8	18.5
3502-5		0.076	0.030	4	T	204	400	802.7	116.5	536.7	77.9	22.0
3502-5		0.076	0.030	5	T	427	800	702.1	101.9	473.3	68.7	21.5
3502-5		0.076	0.030	6	T	427	800	713.8	103.6	486.4	70.6	20.0
3502-5		0.076	0.030	7	T	649	1200	430.6	62.5	359.0	52.1	8.0
3502-5		0.076	0.030	8	T	649	1200	465.1	67.5	363.8	52.8	8.0
3502-5		0.076	0.030	9	T	871	1600	231.5	33.6	231.5	33.6	2.5
3502-5		0.076	0.030	10	T	871	1600	221.9	32.2	221.2	32.1	3.1
3502-5		0.076	0.030	11	T	982	1800	162.6	23.6	162.6	23.6	5.0
3502-5		0.076	0.030	12	T	982	1800	165.4	24.0	165.4	24.0	4.5
3502-5		0.076	0.030	129	L	982	1800	192.2	27.9	182.6	26.5	7.0
3502-5		0.076	0.030	130	L	982	1800	177.8	25.8	176.4	25.6	5.0
3502-5		0.076	0.030	114	45°	982	1800	188.9	27.4	180.5	26.2	5.0
3502-5		0.076	0.030	115	45°	982	1800	186.0	27.0	180.5	26.2	5.0
3502-5		0.076	0.030	13	T	1093	2000	143.3	20.8	143.3	20.8	5.5
3502-5		0.076	0.030	14	T	1093	2000	151.6	22.0	148.8	21.6	4.0
3502-5		0.076	0.030	110	T	1093	2000	134.4	19.5	134.4	19.5	4.0
3502-5		0.076	0.030	B	T	1093	2000	136.4	19.8	136.4	19.8	1.1
3502-5		0.076	0.030	E	T	1093	2000	130.2	18.9	130.2	18.9	1.9
3502-5		0.076	0.030	Q	T	1093	2000	130.2	18.9	130.2	18.9	1.3
3502-5		0.076	0.030	T	T	1093	2000	132.3	19.2	132.3	19.2	1.4
3502-4		0.076	0.030	B	T	1093	2000	130.2	18.9	130.2	18.9	1.8
3502-4		0.076	0.030	E	T	1093	2000	130.2	18.9	130.2	18.9	1.7
3502-4		0.076	0.030	Q	T	1093	2000	130.9	19.0	130.9	19.0	1.6
3502-4		0.076	0.030	T	T	1093	2000	125.4	18.2	124.4	18.2	1.6
3502-5		0.076	0.030	31	L	1093	2000	153.0	22.2	149.5	21.7	4.0
3502-5		0.076	0.030	32	L	1093	2000	157.1	22.8	146.8	21.3	6.5
3502-5		0.076	0.030	106	L	1093	2000	148.8	21.6	139.2	21.2	5.0
3502-5		0.076	0.030	113	L	1093	2000	151.6	22.0	147.4	21.4	5.0
3502-5		0.076	0.030	I	L	1093	2000	137.8	20.0	137.8	20.0	2.0

TABLE C-21

REPRODUCIBILITY TENSILE TEST DATA

Heat No.	Sheet No.	Gauge cm.	Gauge in.	Sample No.	Direction	Test Temp. °C	Test Temp. °F	UTS MN/m²	UTS ksi	YS MN/m²	YS ksi	Elong. %
3502-5		0.076	0.030	L	L	1093	2000	139.9	20.3	139.9	20.3	2.0
3502-5		0.076	0.030	O	L	1093	2000	139.2	20.2	139.2	20.2	1.8
3502-5		0.076	0.030	V	L	1093	2000	142.6	20.7	138.5	20.1	3.0
3502-5		0.076	0.030	Y	L	1093	2000	146.1	21.2	144.0	20.9	2.5
3502-5		0.076	0.030	BB	L	1093	2000	137.1	19.9	135.0	19.6	2.5
3502-4		0.076	0.030	I	L	1093	2000	144.0	20.9	144.0	20.9	1.7
3502-4		0.076	0.030	L	L	1093	2000	137.8	20.0	135.7	19.7	1.9
3502-4		0.076	0.030	O	L	1093	2000	142.6	20.7	140.6	20.4	2.4
3502-4		0.076	0.030	V	L	1093	2000	140.6	20.4	135.7	19.7	2.7
3502-4		0.076	0.030	Y	L	1093	2000	144.7	21.0	144.7	21.0	2.4
3502-4		0.076	0.030	BB	L	1093	2000	142.6	20.7	142.6	20.7	2.5
3502-5		0.076	0.030	37	45°	1093	2000	148.8	21.6	148.1	21.5	3.5
3502-5		0.076	0.030	38	45°	1093	2000	151.6	22.0	148.1	21.5	5.0
3502-5		0.076	0.030	15	T	1204	2200	97.8	14.2	97.8	14.2	2.0
3502-5		0.076	0.030	16	T	1204	2200	104.1	15.1	104.1	15.1	2.0
3502-5		0.076	0.030	131	L	1204	2200	107.5	15.6	107.5	15.6	2.5
3502-5		0.076	0.030	132	L	1204	2200	104.0	15.1	104.0	15.1	2.5
3502-5		0.076	0.030	116	45°	1204	2200	102.7	14.9	102.7	14.9	1.2
3502-5		0.076	0.030	117	45°	1204	2200	102.7	14.9	120.7	14.9	2.5
3502-5		0.076	0.030	141	T	1316	2400	42.0	6.1	35.8	5.2	3.0
3502-5		0.076	0.030	142	T	1316	2400	39.3	5.7	35.8	5.2	3.0

TABLE C-22

REPRODUCIBILITY TENSILE TEST DATA

Heat No.	Sheet No.	Gauge cm.	Gauge in.	Sample No.	Direction	Test Temp. °C	Test Temp. °F	UTS MN/m^2	UTS ksi	YS MN/m^2	YS ksi	Elong. %
3456-19		0.025	0.010	A	T	Room	Room	795.8	115.5	594.6	86.3	12.8
3456-19		0.025	0.010	D	T	Room	Room	832.3	120.8	584.3	84.8	20.0
3456-19		0.025	0.010	P	T	Room	Room	800.6	116.2	577.4	83.8	22.5
3456-19		0.025	0.010	S	T	Room	Room	811.6	117.8	586.3	85.1	19.5
3456-19		0.025	0.010	1	T	Room	Room	804.8	116.8	592.5	86.0	17.5
3456-19		0.025	0.010	2	T	Room	Room	822.7	119.4	602.2	87.4	20.0
3456-19		0.025	0.010	109	T	Room	Room	834.4	121.1	606.3	88.0	17.5
3456-18		0.025	0.010	A	T	Room	Room	848.8	123.2	614.6	89.2	18.3
3456-18		0.025	0.010	D	T	Room	Room	861.9	125.1	631.1	91.6	10.5
3456-18		0.025	0.010	P	T	Room	Room	856.4	124.3	593.2	86.1	20.0
3456-18		0.025	0.010	S	T	Room	Room	794.4	115.3	654.6	95.0	8.1
3456-19		0.025	0.010	H	L	Room	Room	784.8	113.9	603.6	87.6	5.5
3456-19		0.025	0.010	K	L	Room	Room	786.1	114.1	611.8	88.8	4.5
3456-19		0.025	0.010	N	L	Room	Room	827.5	120.1	591.2	85.8	5.0
3456-19		0.025	0.010	U	L	Room	Room	766.9	111.3	580.8	84.5	5.0
3456-19		0.025	0.010	X	L	Room	Room	822.7	119.4	611.1	88.7	7.5
3456-19		0.025	0.010	AA	L	Room	Room	835.8	121.3	518.8	75.3	5.0
3456-19		0.025	0.010	29	L	Room	Room	821.3	119.2	637.3	92.5	5.0
3456-19		0.025	0.010	30	L	Room	Room	822.7	119.4	640.1	92.9	5.0
3456-19		0.025	0.010	105	L	Room	Room	850.2	123.4	653.2	94.8	7.5
3456-19		0.025	0.010	112	L	Room	Room	902.6	131.0	635.3	92.2	15.0
3456-18		0.025	0.010	H	L	Room	Room	834.4	121.1	644.9	93.6	5.6
3456-18		0.025	0.010	K	L	Room	Room	828.9	120.3	622.2	90.3	7.7
3456-18		0.025	0.010	N	L	Room	Room	764.1	110.9	640.8	93.0	7.5
3456-18		0.025	0.010	U	L	Room	Room	782.7	113.6	622.2	90.3	6.0
3456-18		0.025	0.010	X	L	Room	Room	839.2	121.8	634.6	92.1	6.8
3456-18		0.025	0.010	AA	L	Room	Room	814.4	118.2	614.6	89.2	5.6
3456-19		0.025	0.010	35	45°	Room	Room	824.7	119.7	615.3	89.3	10.0
3456-19		0.025	0.010	36	45°	Room	Room	762.7	110.7	608.4	88.3	5.0
3456-19		0.025	0.010	3	T	204	400	712.4	103.4	537.4	78.0	12.5
3456-19		0.025	0.010	4	T	204	400	755.1	109.6	547.1	79.4	19.5

TABLE C-23

REPRODUCIBILITY TENSILE TEST DATA

Heat No.	Sheet No.	Gauge cm.	Gauge in.	Sample No.	Direction	Test Temp. °C	Test Temp. °F	UTS MN/m^2	UTS ksi	YS MN/m^2	YS ksi	Elong. %
3456-19		0.025	0.010	5	T	427	800	647.0	93.9	486.4	70.6	21.5
3456-19		0.025	0.010	6	T	427	800	647.0	93.9	507.8	73.7	20.0
3456-19		0.025	0.010	7	T	649	1200	398.9	57.9	381.7	55.4	5.0
3456-19		0.025	0.010	8	T	649	1200	390.7	56.7	366.5	53.2	2.5
3456-19		0.025	0.010	9	T	871	1600	226.0	32.8	222.5	32.3	2.5
3456-19		0.025	0.010	10	T	871	1600	229.4	33.3	229.4	33.3	1.6
3456-19		0.025	0.010	11	T	982	1800	159.2	23.1	159.2	23.1	2.5
3456-19		0.025	0.010	12	T	982	1800	172.3	25.0	172.3	25.0	3.5
3456-19		0.025	0.010	129	L	982	1800	174.3	25.3	174.3	25.3	2.0
3456-19		0.025	0.010	130	L	982	1800	176.4	25.6	176.4	25.6	2.0
3456-19		0.025	0.010	114	45°	982	1800	160.5	23.3	160.5	23.3	2.0
3456-19		0.025	0.010	115	45°	982	1800	174.3	25.3	174.3	25.3	2.0
3456-19		0.025	0.010	13	T	1093	2000	133.7	19.4	133.7	19.4	3.0
3456-19		0.025	0.010	14	T	1093	2000	130.9	19.0	130.9	19.0	3.0
3456-19		0.025	0.010	110	T	1093	2000	102.0	14.8	102.0	14.8	2.0
3456-19		0.025	0.010	B	T	1093	2000	142.6	20.7	142.6	20.7	2.0
3456-19		0.025	0.010	E	T	1093	2000	130.9	19.0	130.9	19.0	2.5
3456-19		0.025	0.010	Q	T	1093	2000	137.1	19.9	137.1	19.9	2.5
3456-19		0.025	0.010	T	T	1093	2000	146.1	21.2	146.1	21.2	2.5
3456-18		0.025	0.010	B	T	1093	2000	126.8	18.4	126.8	18.4	1.5
3456-18		0.025	0.010	E	T	1093	2000	128.8	18.7	128.8	18.7	2.5
3456-18		0.025	0.010	Q	T	1093	2000	128.2	18.6	128.2	18.6	3.0
3456-18		0.025	0.010	T	T	1093	2000	133.7	19.4	133.7	19.4	1.0
3456-19		0.025	0.010	31	L	1093	2000	135.0	19.6	135.0	19.6	2.5
3456-19		0.025	0.010	32	L	1093	2000	106.8	15.5	106.8	15.5	2.5
3456-19		0.025	0.010	106	L	1093	2000	135.8	19.7	135.8	19.7	2.5
3456-19		0.025	0.010	113	L	1093	2000	137.1	19.9	137.1	19.9	1.5
3456-19		0.025	0.010	I	L	1093	2000	126.1	18.3	126.1	18.3	2.5
3456-19		0.025	0.010	L	L	1093	2000	144.7	21.0	144.7	21.0	2.5

TABLE C-24

REPRODUCIBILITY TENSILE TEST DATA

Heat No.	Sheet No.	Gauge cm.	Gauge in.	Sample No.	Direction	Test Temp. °C	Test Temp. °F	UTS MN/m²	UTS ksi	YS MN/m²	YS ksi	Elong. %
3456-19		0.025	0.010	O	L	1093	2000	121.3	17.6	121.3	17.6	3.0
3456-19		0.025	0.010	V	L	1093	2000	122.6	17.8	122.6	17.8	2.5
3456-19		0.025	0.010	Y	L	1093	2000	-	(2)	-	-	-
3456-19		0.025	0.010	BB	L	1093	2000	139.2	20.2	139.2	20.2	3.5
3456-18		0.025	0.010	I	L	1093	2000	118.5	17.2	118.5	17.2	1.5
3456-18		0.025	0.010	L	L	1093	2000	132.3	19.2	132.3	19.2	1.0
3456-18		0.025	0.010	O	L	1093	2000	136.4	19.8	136.4	19.8	2.5
3456-18		0.025	0.010	V	L	1093	2000	135.0	19.6	135.0	19.6	4.0
3456-18		0.025	0.010	Y	L	1093	2000	121.3	17.6	121.3	17.6	2.5
3456-18		0.025	0.010	BB	L	1093	2000	135.0	19.6	135.0	19.6	2.5
3456-19		0.025	0.010	37	45°	1093	2000	140.6	20.4	140.6	20.4	2.0
3456-19		0.025	0.010	38	45	1093	2000	-	(2)	-	-	-
3456-19		0.025	0.010	15	T	1204	2200	87.5	12.7	87.5	12.7	1.1
3456-19		0.025	0.010	16	T	1204	2200	88.2	12.8	88.2	12.8	2.5
3456-19		0.025	0.010	131	L	1204	2200	82.7	12.0	82.7	12.0	2.0
3456-19		0.025	0.010	132	L	1204	2200	95.8	13.9	95.8	13.9	1.5
3456-19		0.025	0.010	116	45°	1204	2200	79.9	11.6	79.9	11.6	2.5
3456-19		0.025	0.010	117	45°	1204	2200	90.9	13.2	90.9	13.2	2.5
3456-19		0.025	0.010	141	T	1316	2400	49.6	7.2	37.2	5.4	5.0
3456-19		0.025	0.010	142	T	1316	2400					

TABLE C-25

REPRODUCIBILITY TENSILE TEST DATA

Heat No.	Sheet No.	Gauge cm.	Gauge in.	Sample No.	Direction	Test Temp. °C	Test Temp. °F	UTS MN/m^2	UTS ksi	YS MN/m^2	YS ksi	Elong. %
3456-7		0.051	0.020	A	T	Room	Room	862.6	125.2	572.6	83.1	22.5
3456-7		0.051	0.020	D	T	Room	Room	858.5	124.6	600.8	87.2	22.5
3456-7		0.051	0.020	P	T	Room	Room	819.9	119.0	525.0	76.2	14.5
3456-7		0.051	0.020	S	T	Room	Room	580.9	123.5	575.3	83.5	24.0
3456-7		0.051	0.020	1	T	Room	Room	895.7	130.0	592.5	86.0	22.0
3456-7		0.051	0.020	2	T	Room	Room	910.2	132.1	602.9	87.5	22.5
3456-7		0.051	0.020	109	T	Room	Room	904.0	131.2	599.4	87.0	21.5
3456-6		0.051	0.020	A	T	Room	Room	807.5	117.2	567.7	82.4	23.5
3456-6		0.051	0.020	D	T	Room	Room	798.6	115.9	579.4	84.1	22.4
3456-6		0.051	0.020	P	T	Room	Room	807.5	117.2	560.2	81.3	22.1
3456-6		0.051	0.020	S	T	Room	Room	845.4	122.7	518.8	75.3	22.5
3456-6		0.051	0.020	H	L	Room	Room	913.6	132.6	609.8	88.5	17.5
3456-7		0.051	0.020	K	L	Room	Room	941.2	136.6	622.2	90.3	16.4
3456-7		0.051	0.020	N	L	Room	Room	937.0	136.0	620.1	90.0	19.5
3456-7		0.051	0.020	U	L	Room	Room	904.7	131.3	562.9	81.7	17.5
3456-7		0.051	0.020	X	L	Room	Room	921.2	133.7	619.4	89.9	17.5
3456-7		0.051	0.020	AA	L	Room	Room	904.7	131.3	591.9	85.9	18.0
3456-7		0.051	0.020	29	L	Room	Room	969.4	140.7	620.8	90.1	17.4
3456-7		0.051	0.020	30	L	Room	Room	949.4	137.8	622.9	90.4	12.5
3456-7		0.051	0.020	105	L	Room	Room	974.9	141.5	621.5	90.2	16.7
3456-7		0.051	0.020	112	L	Room	Room	954.3	138.5	620.1	90.0	12.5
3456-6		0.051	0.020	H	L	Room	Room	874.3	126.9	570.5	82.8	18.1
3456-6		0.051	0.020	K	L	Room	Room	899.1	130.5	578.8	84.0	17.5
3456-6		0.051	0.020	N	L	Room	Room	879.9	127.7	573.9	83.3	18.3
3456-6		0.051	0.020	U	L	Room	Room	864.7	125.5	567.7	82.4	17.5
3456-6		0.051	0.020	X	L	Room	Room	839.9	121.9	530.5	77.0	14.8
3456-6		0.051	0.020	AA	L	Room	Room	861.3	125.0	558.8	81.1	19.9
3456-7		0.051	0.020	35	45°	Room	Room	915.7	132.9	629.1	91.3	17.5
3456-7		0.051	0.020	36	45°	Room	Room	898.5	130.4	616.0	89.4	30.0

TABLE C-26

REPRODUCIBILITY TENSILE TEST DATA

Heat No.	Sheet No.	Gauge cm.	Gauge in.	Sample No.	Direction	Test Temp. °C	Test Temp. °F	UTS MN/m²	UTS ksi	YS MN/m²	YS ksi	Elong. %
3456-7		0.051	0.020	3	T	204	400	813.0	118.0	499.5	72.5	16.5
3456-7		0.051	0.020	4	T	204	400	767.5	111.4	488.5	70.9	15.0
3456-7		0.051	0.020	5	T	427	800	726.2	105.4	485.1	70.4	20.0
3456-7		0.051	0.020	6	T	427	800	743.4	107.9	493.3	71.6	19.5
3456-7		0.051	0.020	7	T	649	1200	458.2	66.5	370.0	53.7	7.5
3456-7		0.051	0.020	8	T	649	1200	451.3	65.5	358.3	52.0	10.0
3456-7		0.051	0.020	9	T	871	1600	230.8	33.5	223.2	32.4	2.6
3456-7		0.051	0.020	10	T	871	1600	233.6	33.9	229.4	33.3	3.0
3456-7		0.051	0.020	11	T	982	1800	186.7	27.1	184.0	26.7	3.0
3456-7		0.051	0.020	12	T	982	1800	162.6	23.6	162.6	23.6	2.0
3456-7		0.051	0.020	129	L	982	1800	184.7	26.8	181.9	26.4	4.0
3456-7		0.051	0.020	130	L	982	1800	175.0	25.4	175.0	25.4	3.0
3456-7		0.051	0.020	114	45°	982	1800	184.7	26.8	180.5	26.2	2.5
3456-7		0.051	0.020	115	45°	982	1800	187.4	27.2	184.7	26.8	3.5
3456-7		0.051	0.020	13	T	1093	2000	146.8	21.3	148.8	21.3	2.5
3456-7		0.051	0.020	14	T	1093	2000	136.4	19.8	136.4	19.8	4.0
3456-7		0.051	0.020	110	T	1093	2000	146.8	21.3	146.8	21.3	3.5
3456-7		0.051	0.020	B	T	1093	2000	130.2	18.9	130.2	18.9	1.0
3456-7		0.051	0.020	E	T	1093	2000	126.8	18.4	126.8	18.4	1.0
3456-7		0.051	0.020	Q	T	1093	2000	133.0	19.3	133.0	19.3	2.3
3456-7		0.051	0.020	T	T	1093	2000	143.3	20.8	143.3	20.8	2.5
3456-6		0.051	0.020	B	T	1093	2000	119.2	17.3	119.2	17.3	1.3
3456-6		0.051	0.020	E	T	1093	2000	119.9	17.4	119.9	17.4	2.0
3456-6		0.051	0.020	Q	T	1093	2000	123.3	17.9	123.3	17.9	1.0
3456-6		0.051	0.020	T	T	1093	2000	124.0	18.0	124.0	18.0	1.5
3456-7		0.051	0.020	31	L	1093	2000	153.0	22.2	153.0	22.2	4.0
3456-7		0.051	0.020	32	L	1093	2000	153.7	22.3	153.7	22.3	2.5
3456-7		0.051	0.020	106	L	1093	2000	151.6	22.0	148.8	21.6	3.0
3456-7		0.051	0.020	113	L	1093	2000	150.9	21.9	148.1	21.5	3.0

TABLE C-27

REPRODUCIBILITY TENSILE TEST DATA

Heat No.	Sheet No.	Gauge cm.	Gauge in.	Sample No.	Direction	Test Temp. °C	Test Temp. °F	UTS MN/m^2	UTS ksi	YS MN/m^2	YS ksi	Elong. %
3456-7		0.051	0.020	I	L	1093	2000	139.9	20.3	137.1	19.9	2.4
3456-7		0.051	0.020	L	L	1093	2000	129.5	18.8	129.5	18.8	2.3
3456-7		0.051	0.020	O	L	1093	2000	139.2	20.2	133.0	19.3	2.2
3456-7		0.051	0.020	V	L	1093	2000	144.0	20.9	142.6	20.7	2.2
3456-7		0.051	0.020	Y	L	1093	2000	146.8	21.3	146.8	21.3	2.0
3456-7		0.051	0.020	BB	L	1093	2000	145.4	21.1	145.4	21.1	2.5
3456-6		0.051	0.020	I	L	1093	2000	144.0	20.9	139.9	20.3	2.4
3456-6		0.051	0.020	L	L	1093	2000	146.8	21.3	146.8	21.3	2.0
3456-6		0.051	0.020	O	L	1093	2000	136.4	19.8	124.0	18.0	1.9
3456-6		0.051	0.020	V	L	1093	2000	136.4	19.8	135.0	19.6	2.1
3456-6		0.051	0.020	Y	L	1093	2000	139.9	20.3	139.9	20.3	2.3
3456-6		0.051	0.020	BB	L	1093	2000	137.1	19.9	133.0	19.3	2.2
3456-7		0.051	0.020	37	45°	1093	2000	148.8	21.6	148.8	21.6	2.5
3456-7		0.051	0.020	38	45°	1093	2000	126.1	18.3	126.1	18.3	2.5
3456-7		0.051	0.020	15	T	1204	2200	97.1	14.1	97.1	14.1	2.5
3456-7		0.051	0.020	16	T	1204	2200	86.1	12.5	86.1	12.5	2.5
3456-7		0.051	0.020	131	L	1204	2200	112.3	16.3	110.2	16.0	3.6
3456-7		0.051	0.020	132	L	1204	2200	109.6	15.9	108.9	15.8	2.6
3456-7		0.051	0.020	116	45°	1204	2200	95.1	13.8	95.1	13.8	2.5
3456-7		0.051	0.020	117	45°	1204	2200	104.0	15.1	104.0	15.1	2.5
3456-7		0.051	0.020	141	T	1316	2400	56.5	8.2	56.5	8.2	1.0
3456-7		0.051	0.020	142	T	1316	2400	52.4	7.6	51.0	7.4	1.0

APPENDIX D

TDNiCr SHEET SHIPMENTS

TABLE D-1

FIRST SHIPMENT

TDNiCr SHEET INVENTORY

Quantity Pcs.	Size (cm.)	Wt. kg.	Heat No.	Serial No.	Finish
1	0.203x55.88x60.96	6.40	3321-1	10	Ground
1	0.051x38.10x101.60	1.72	3321-1	36	"
1	0.051x35.56x71.12	1.09	3321-2	39	"
1	0.051x40.64x60.32	1.09	3321-3	37	"
1	0.051x36.83x65.40	1.04	3321-3	38	"
1	0.051x41.91x71.12	1.27	3321-2	40	"
1	0.051x42.54x95.88	1.81	3321-2	9	"
1	0.051x42.54x94.61	1.72	3321-2	8	"
1	0.051x55.88x121.92	5.40	3321-1	-	"
1	0.051x53.34x111.76		3321-1	-	"
SUB-TOTAL 10 pcs.		21.55	3321	38,554.75 Cm^2	
1	0.025x34.29x72.39	0.59	3322-3	23	Pickle-Roll
1	0.025x24.29x71.12	0.54	3322-3	24	"
1	0.025x24.29x72.39	0.59	3322-3	25	"
1	0.025x24.29x72.39	0.59	3322-3	26	"
1	0.025x24.29x72.39	0.59	3322-3	27	"
1	0.025x24.29x72.39	0.59	3322-3	28	"
1	0.025x24.29x72.39	0.59	3322-3	29	"
1	0.025x24.29x71.12	0.54	3322-3	30	"
1	0.038x42.54x70.48	0.95	3322-4	18	Ground
1	0.038x42.54x76.20	1.09	3322-4	19	"
1	0.102x46.99x123.19	5.35	3322-1	15	"
1	0.152x41.27x48.26	2.63	3322-2	1	"
SUB-TOTAL 12 pcs.		14.65	3322	33,816.69 Cm^2	
1	0.038x48.26x117.79	1.81	3323-4	20	Ground
1	0.064x35.56x63.50	1.22	3323-2	7	"
1	0.038x48.58x115.25	1.86	3323-4	16	"
1	0.038x48.89x114.93	1.77	3323-4	17	"
1	0.064x43.81x73.98	1.81	3323-3	3	"
1	0.064x43.50x74.29	1.77	3323-3	2	"
1	0.064x37.46x99.38	2.00	3323-1	6	"
1	0.064x43.50x98.42	2.00	3323-1	5	"
1	0.064x36.83x101.60	2.09	3323-1	4	"
1	0.038x45.72x106.68	1.72	3323-4	21	"
SUB-TOTAL 10 pcs		18.05	3323	41,713.45 Cm^2	

TABLE D-1

FIRST SHIPMENT

TDNiCr SHEET INVENTORY

Quantity Pcs.	Size(in.)	Wt. #	Heat No.	Serial No.	Finish
1	0.080x22x24	14.1	3321-1	10	Ground
1	0.020x15x40	3.8	3321-1	36	"
1	0.020x14x28	2.4	3321-2	39	"
1	0.020x16x23-3/4	2.4	3321-3	37	"
1	0.020x14-1/2x25-3/4	2.3	3321-3	38	"
1	0.020x16-1/2x28	2.8	3321-2	40	"
1	0.020x16-3/4x37-3/4	4.0	3321-2	9	"
1	0.020x16-3/4x37-1/4	3.8	3321-2	8	"
1	0.020x22x48	11.9	3321-1	-	"
1	0.020x21x44		3321-1	-	"
SUB-TOTAL 10 pcs.		47.5	3321	41.5 sq.ft.	
1	0.010x13-1/2x28-1/2	1.3	3322-3	23	Pickle-Roll
1	0.010x13-1/2x28	1.2	3322-3	24	"
1	0.010x13-1/2x28-1/2	1.3	3322-3	25	"
1	0.010x13-1/2x28-1/2	1.3	3322-3	26	"
1	0.010x13-1/2x28-1/2	1.3	3322-3	27	"
1	0.010x13-1/2x28-1/2	1.3	3322-3	28	"
1	0.010x13-1/2x28-1/2	1 3	3322-3	29	"
1	0.010x13-1/2x28	1.2	3322-3	30	"
1	0.015x16-3/4x27-3/4	2.1	3322-4	18	Ground
1	0.015x16-3/4x30	2.4	3322-4	19	"
1	0.040x18-1/2x48-1/2	11.8	3322-1	15	Ground
1	0.060x16-1/4x19	5.8	3322-2	1	Ground
SUB-TOTAL 12 pcs.		32.3	3322	36.4 sq.ft.	
1	0.015x19x46-3/8	4.0	3323-4	20	Ground
1	0.025x14x25	2.7	3323-2	7	Ground
1	0.015x19-1/8x45-3/8	4.1	3323-4	16	Ground
1	0.015x19-1/4x45-1/4	3.9	3323-4	17	"
1	0.025x17-1/4x29-1/8	4.0	3323-3	3	Ground
1	0.025x17-1/8x29-1/4	3.9	3323-3	2	"
1	0.025x14-3/4x39-1/8	4.4	3323-1	6	"
1	0.025x14-3/4x38-3/4	4.4	3323-1	5	"
1	0.025x14-1/2x40	4.6	3323-1	4	"
1	0.015x18x42	3.8	3323-4	21	Ground
SUB-TOTAL 10 pcs.		39.8	3323	44.9 sq.ft.	

TABLE D-1
(CONT'D)

FIRST SHIPMENT

TDNiCr SHEET INVENTORY

Quantity Pcs.	Size(cm.)	Wt. kg.	Heat No.	Serial No.	Finish
1	0.025x40.64x101.60	0.95	3324-4	33	Pickle-Roll
1	0.025x40.64x101.60	0.95	3324-4	31	"
1	0.025x40.64x101.60	0.90	3324-4	32	"
1	0.025x38.42x46.35	0.36	3324-4	41	Ground
1	0.025x38.73x85.09	0.73	3324-4	42	"
1	0.025x38.73x85.09	0.73	3324-4	43	"
1	0.025x41.91x74.93	0.68	3324-4	44	"
1	0.025x33.02x103.50	0.77	3324-4	34	Pickle-Roll
1	0.038x31.75x72.39	0.82	3324-1	45	Ground
1	0.038x40.64x45.72	0.68	3324-1	46	"
SUB-TOTAL 10 pcs		7.57	3324	31,494.12 Cm^2	
1	0.640x25.40x60.96	9.16	3325	14	Ground
1	0.152x43.18x83.82	4.81	3325	22	"
1	0.640x10.16x60.96	3.67	3325	11	"
1	0.640x36.19x15.24	3.27	3325	12	"
SUB-TOTAL 4 pcs		20.91	3325	6,317.40 Cm^2	
GRAND TOTAL 46 pcs.		82.69		151,896.41 Cm^2	

TABLE D-1
(CONT'D)

FIRST SHIPMENT

TDNiCr SHEET INVENTORY

Quantity Pcs.	Size(in.)	Wt. #	Heat No.	Serial No.	Finish
1	0.010x16x40	2.1	3324-4	33	Pickle-Roll
1	0.010x16x40	2.1	3324-4	31	"
1	0.010x16x40	2.0	3324-4	32	"
1	0.010x15-1/8x18-1/4	0.8	3324-4	41	Ground
1	0.010x15-1/4x33-1/2	1.6	3324-4	42	"
1	0.010x15-1/4x33-1/2	1.6	3324-4	43	"
1	0.010x16-1/2x29-1/2	1.5	3324-4	44	"
1	0.010x13x40-3/4	1.7	3324-4	34	Pickle-Roll
1	0.015x12-1/2x28-1/2	1.8	3324-1	45	Ground
1	0.015x16x18	1.5	3324-1	46	"
SUB-TOTAL 10 pcs		16.7	3324	33.9 sq.ft.	
1	0.250x10x24	20.2	3325	14	Ground
1	0.060x17x33	10.6	3325	22	Ground
1	0.250x4x24	8.1	3325	11	Ground
1	0.250x14-1/4x6	7.2	3325	12	"
SUB-TOTAL 4 pcs		46.1	3325	6.8 sq.ft.	
GRAND TOTAL 46 pcs.		182.4		163.5 sq.ft.	

TABLE D-2

SECOND SHIPMENT

TDNiCr SHEET INVENTORY

Quantity Pcs.	Size (cm.)	Wt. kg.	Heat No.	Serial No.	Finish
1	0.025x46.35x89.53	0.86	3387	81	Ground
1	0.025x43.18x118.74	1.04	3387	86	Ground
1	0.025x46.35x89.53	0.91	3387	89	Pick-Roll
1	0.025x46.35x89.53	0.91	3387	90	Pick-Roll
1	0.025x38.42x71.75	0.64	3387	92	Pick-Roll
1	0.025x46.35x89.53	0.95	3387	93	Pick-Roll
1	0.025x37.15x76.20	0.64	3387	94	Pick-Roll
1	0.025x44.13x86.99	0.86	3387	95	Pick-Roll
1	0.025x44.45x95.88	0.91	3387	101	Pick-Roll
1	0.025x40.64x98.42	0.91	3387	103	Pick-Roll
1	0.025x45.72x86.99	0.95	3387	105	Pick-Roll
1	0.025x44.45x77.47	0.59	3387	107	Ground
SUB-TOTAL 12 pcs.		10.16	3387	46,916.02 Cm^2	
1	0.025x46.99x127.63	1.32	3382	106	Ground
1	0.025x46.35x114.93	1.13	3382	108	Ground
1	0.025x43.18x63.82	0.54	3382	109A	Ground
1	0.025x37.78x52.70	0.41	3382	109B	Ground
1	0.025x39.69x86.68	0.68	3382	118	Ground
1	0.025x38.42x48.26	0.36	3382	119	Ground
1	0.025x43.02x98.42	0.82	3382	120	Ground
1	0.025x43.18x64.77	0.54	3382	121	Ground
1	0.025x39.37x35.88	0.32	3382	123	Ground
1	0.025x42.86x61.28	0.50	3382	125	Pick-Roll
SUB-TOTAL 10 pcs.		6.62	3382	32,423.15 Cm^2	
1	0.025x46.35x114.93	1.22	3416	80	Pick-Roll
1	0.025x38.73x94.30	0.77	3416	82	Ground
1	0.025x48.89x132.71	1.32	3416	83	Ground
1	0.025x45.72x128.90	1.32	3416	84	Pick-Roll
1	0.025x48.58x127.00	1.41	3416	88	Pick-Roll
1	0.025x45.72x100.97	0.91	3416	91	Ground
1	0.025x47.31x93.98	0.95	3416	99	Ground
1	0.025x47.62x92.07	0.86	3416	100	Ground
1	0.025x47.62x93.98	0.91	3416	110	Ground
1	0.025x47.31x93.98	0.95	3416	111	Ground
1	0.025x39.37x95.98	0.86	3416	112	Ground
1	0.025x45.08x100.65	0.86	3416	113	Ground
1	0.025x33.81x83.82	0.77	3416	114	Ground
1	0.025x47.31x128.27	1.22	3416	115	Ground
1	0.025x45.08x128.90	1.18	3416	116	Ground
SUB-TOTAL 15 pcs.		15.51	3416	73,764.98 Cm^2	

TABLE D-2

SECOND SHIPMENT

TDNiCr SHEET INVENTORY

Quantity Pcs.	Size(in.)	Wt. #	Heat	Serial No.	Finish
1	0.010x18-1/4x35-1/4	1.9	3387	81	Ground
1	0.010x17x46-3/4	2.3	3387	86	Ground
1	0.010x18-1/4x35-1/4	2.0	3387	89	Pick-Roll
1	0.010x18-1/4x35-1/4	2.0	3387	90	Pick-Roll
1	0.010x15-1/8x28-1/4	1.4	3387	92	Pick-Roll
1	0.010x18-1/4x35-1/4	2.1	3387	93	Pick-Roll
1	0.010x14-5/8x30	1.4	3387	94	Pick-Roll
1	0.010x17-3/8x34-1/4	1.9	3387	95	Pick-Roll
1	0.010x17-1/2x37-3/4	2.0	3387	101	Pick-Roll
1	0.010x16x38-3/4	2.0	3387	103	Pick-Roll
1	0.010x18x34-1/4	2.1	3387	105	Pick-Roll
1	0.010x17-1/2x30-1/2	1.3	3387	107	Ground
SUB-TOTAL 12 pcs		22.4	3387	50.5 sq.ft.	
1	0.010x18-1/2x50-1/4	2.9	3382	106	Ground
1	0.010x18-1/4x45-1/4	2.5	3382	108	Ground
1	0.010x17x25-1/8	1.2	3382	109A	Ground
1	0.010x14-7/8x20-3/4	0.9	3382	109B	Ground
1	0.010x15-5/8x34-1/8	1.5	3382	118	Ground
1	0.010x15-1/8x19	0.8	3382	119	Ground
1	0.010x16-15/16x38-3/4	1.8	3382	120	Ground
1	0.010x17x25-1/2	1.2	3382	121	Ground
1	0.010x15-1/2x14-1/8	0.7	3382	123	Ground
1	0.010x16-7/8x24-1/8	1.1	3382	125	Pick-Roll
SUB-TOTAL 10 pcs		14.6	3382	34.9 sq.ft.	
1	0.010x18-1/4x45-1/4	2.7	3416	80	Pick-Roll
1	0.010x15-1/4x37-1/8	1.7	3416	82	Ground
1	0.010x19-1/4x52-1/4	2.9	3416	83	Ground
1	0.010x18x50-3/4	2.9	3416	84	Pick-Roll
1	0.010x19-1/8x50	3.1	3416	88	Pick-Roll
1	0.010x18x39-3/4	2.0	3416	91	Ground
1	0.010x18-5/8x37	2.1	3416	99	Ground
1	0.010x18-3/4x36-1/4	1.9	3416	100	Ground
1	0.010x18-3/4x37	2.0	3416	110	Ground
1	0.010x18-5/8x37	2.1	3416	111	Ground
1	0.010x15-1/2x37-3/4	1.9	3416	112	Ground
1	0.010x17-3/4x39-5/8	1.9	3416	113	Ground
1	0.010x17-1/4x33	1.7	3416	114	Ground
1	0.010x18-5/8x50-1/2	2.7	3416	115	Ground
1	0.010x17-3/4x50-3/4	2.6	3416	116	Ground
SUB-TOTAL 15 pcs		34.2	3416	79.4 sq.ft.	

TABLE D-2
(CONT'D)

SECOND SHIPMENT

TDNiCr SHEET INVENTORY

Quantity Pcs.	Size(cm.)	Wt. kg.	Heat No.	Serial No.	Finish
1	0.640x36.83x80.96	13.93	3384	117	Ground
SUB-TOTAL 1 pc		13.93	3384	2,972.90 Cm^2	
1	0.038x46.35x109.85	1.68	3361	62	Ground
1	0.038x45.72x122.55	1.77	3361	63	Ground
1	0.038x42.86x104.46	1.45	3361	64	Ground
1	0.038x42.86x124.46	1.77	3361	65	Ground
1	0.038x47.94x83.82	1.22	3361	66	Ground
1	0.038x47.62x44.13	0.68	3361	67A	Ground
1	0.038x47.62x68.58	1.04	3361	67B	Ground
1	0.038x45.72x89.53	1.27	3361	76	Pick-Roll
1	0.038x45.72x93.98	1.36	3361	78	Pick-Roll
1	0.038x45.72x90.17	1.32	3361	79	Pick-Roll
SUB-TOTAL 10 pcs		13.56	3361	42,270.87 Cm^2	
1	0.660/0.740x55.56x36.83	12.20	3472-1	126	Ground
1	0.660/0.740x54.61x36.83	12.02	3472-2	127	Ground
SUB-TOTAL 2 pcs		24.22	3472	4,087.73 Cm^2	
GRAND TOTAL 50 pcs		83.96		202,435.64 Cm^2	

TABLE D-2
(CONT'D)

SECOND SHIPMENT

TDNiCr SHEET INVENTORY

Quantity Pcs.	Size(in.)	Wt. #	Heat No.	Serial No.	Finish
1	0.250x14-1/2x31-7/8	30.7	3384	117	Ground
SUB-TOTAL 1 pc		30.7	3384	3.2 sq.ft.	
1	0.015x18-1/4x43-1/4	3.7	3361	62	Ground
1	0.015x18x48-1/4	3.9	3361	63	"
1	0.015x16-7/8x41-1/8	3.2	3361	64	"
1	0.015x16-7/8x49	3.9	3361	55	"
1	0.015x18-7/8x33	2.7	3361	66	"
1	0.015x18-3/4x17-3/8	1.5	3361	67A	"
1	0.015x18-3/4x27	2.3	3361	67B	"
1	0.015x18x35-1/4	2.8	3361	76	Pick-Roll
1	0.015x18x37	3.0	3361	78	"
1	0.015x18x35-1/2	2.9	3361	79	"
SUB-TOTAL 10 pcs		29.9	3361	45.5 sq.ft.	
1	.260/.290x21-7/8x14-1/2	26.9	3472-1	126	Ground
1	.260/.290x21-1/2x14-1/2	26.5	3472-2	127	"
SUB-TOTAL 2 pcs		53.4	3472	4.4 sq.ft.	
GRAND TOTAL 50 pcs.		185.2		217.9 sq.ft.	

TABLE D-3

THIRD SHIPMENT

TDNiCr SHEET INVENTORY

Quantity Pcs.	Size (cm.)	Wt. kg.	Heat No.	Serial No.	Finish
1	0.025x38.10x82.23	0.64	3419	141	Cold-Rolled-
1	0.025x42.54x61.28	0.54	3419	140	Annealed
1	0.025x35.56x105.41	0.86	3419	139	"
1	0.025x45.72x104.14	1.13	3419	138	"
1	0.025x42.23x90.80	0.82	3419	137	"
1	0.025x40.32x99.06	0.82	3419	135	"
1	0.025x36.83x99.69	0.77	3419	134	"
1	0.025x42.54x93.66	0.82	3419	133	"
1	0.025x42.54x92.71	0.82	3419	132	"
1	0.025x41.91x52.39	0.45	3419	131A	"
1	0.025x41.91x37.46	0.32	3419	131B	"
1	0.025x45.08x108.90	1.13	3419	130	"
1	0.025x42.54x92.71	0.82	3419	129	"
1	0.025x41.91x99.69	0.91	3419	128	"
SUB-TOTAL	14 pcs.	10.84	3419	50,446.33 Cm^2	
1	0.025x42.86x94.61	0.86	3414	159	Cold Rolled-
1	0.025x42.86x94.30	0.86	3414	158	Annealed
1	0.025x40.64x97.79	0.77	3414	157	"
1	0.025x42.86x57.78	0.50	3414	156	"
1	0.025x45.72x38.10	0.36	3414	155	"
1	0.025x45.72x39.37	0.36	3414	154	"
1	0.025x35.56x38.10	0.27	3414	153	"
1	0.025x45.40x38.10	0.41	3414	152	"
1	0.025x38.10x93.98	0.73	3414	151	"
1	0.025x42.86x94.61	0.82	3414	150	"
1	0.025x39.37x82.55	0.68	3414	149	"
1	0.025x39.37x73.02	0.59	3414	148	"
1	0.025x39.69x73.66	0.64	3414	147	"
1	0.025x39.37x74.93	0.64	3414	146	"
SUB-TOTAL	14 pcs	8.48	3414	40,784.42 Cm^2	
1	0.025x38.42x91.44	0.73	3435	177	Cold Rolled-
1	0.025x38.42x100.97	0.82	3435	176	Annealed
1	0.025x44.45x78.42	0.73	3435	175	"
1	0.025x44.45x79.99	0.77	3435	174	"
1	0.025x38.10x68.58	0.54	3435	172	"
1	0.025x38.42x95.25	0.77	3435	169	"
1	0.025x42.23x61.28	0.54	3435	166	"
1	0.025x39.37x91.76	0.77	3435	165	"
1	0.025x43.81x79.37	0.73	3435	164	"
1	0.025x38.73x101.60	0.86	3435	163	"
1	0.025x40.00x93.98	0.77	3435	161	"
1	0.025x38.42x94.61	0.77	3435	160	"

TABLE D-3

THIRD SHIPMENT

TDNiCr SHEET INVENTORY

Quantity Pcs.	Size(in.)	Wt. #	Heat No.	Serial No.	Finish
1	0.010x15x32-3/8	1.4	3419	141	Cold Rolled-Annealed
1	0.010x16-3/4x24-1/8	1.2	3419	140	"
1	0.010x14-41-1/2	1.9	3419	139	"
1	0.010x18x41	2.5	3419	138	"
1	0.010x16-5/8x35-3/4	1.8	3419	137	"
1	0.010x15-7/8x39	1.8	3419	135	"
1	0.010x14-1/2x39-1/4	1.7	3419	134	"
1	0.010x16-3/4x36-7/8	1.8	3419	133	"
1	0.010x16-3/4x36-1/2	1.8	3419	132	"
1	0.010x16-1/2x20-5/8	1.0	3419	131A	"
1	0.010x16-1/2x14-3/4	0.7	3419	131B	"
1	0.010x17-3/4x42-7/8	2.5	3419	130	"
1	0.010x16-3/4x36-1/2	1.8	3419	129	"
1	0.010x16-1/2x39-1/4	2.0	3419	128	"
SUB-TOTAL 14 pcs.		23.9	3419	54.3 sq.ft.	
1	0.010x16-7/8x37-1/4	1.9	3414	159	Cold Rolled-Annealed
1	0.010x16-7/8x37-1/8	1.9	3414	158	"
1	0.010x16x38-1/2	1.7	3414	157	"
1	0.010x16-7/8x22-3/4	1.1	3414	156	"
1	0.010x18x15	0.8	3414	155	"
1	0.010x18x15-1/2	0.8	3414	154	"
1	0.010x14x15	0.6	3414	153	"
1	0.010x17-7/8x15	0.9	3414	152	"
1	0.010x15x37	1.6	3414	151	"
1	0.010x16-7/8x37-1/4	1.8	3414	150	"
1	0.010x15-1/2x32-1/2	1.5	3414	149	"
1	0.010x15-1/2x28-3/4	1.3	3414	148	"
1	0.010x15-5/8x29	1.4	3414	147	"
1	0.010x15-1/2x29-1/2	1.4	3414	146	"
SUB-TOTAL 14 pcs.		18.7	3414	43.9 sq.ft.	
1	0.010x15-1/8x36	1.6	3435	177	Cold Rolled-Annealed
1	0.010x15-1/8x39-3/4	1.8	3435	176	"
1	0.010x17-1/2x30-7/8	1.6	3435	175	"
1	0.010x17-1/2x31-1/2	1.7	3435	174	"
1	0.010x15x27	1.2	3435	172	"
1	0.010x15-1/8x37-1/2	1.7	3435	169	"
1	0.010x16-5/8x24-1/8	1.2	3435	166	"
1	0.010x15-1/2x36-1/8	1.7	3435	165	"
1	0.010x17-1/4x33-1/4	1.6	3435	164	"
1	0.010x15-1/4x40-1/8	1.9	3435	163	"
1	0.010x15-3/4x37	1.7	3435	161	"

TABLE D-3
(CONT'D)

THIRD SHIPMENT

TDNiCr SHEET INVENTORY

Quantity Pcs.	Size (cm.)	Wt. kg.	Heat No.	Serial No.	Finish
1	0.025x37.78x93.98	0.77	3435	144	Cold Rolled-
1	0.025x45.40x78.74	0.77	3435	143	Annealed
1	0.025x45.72x78.42	0.77	3435	142	"
SUB-TOTAL 15 pcs		11.11	3435	52,676.00 Cm^2	
1	0.025x42.54x88.90	0.86	3436	191	Cold Rolled
1	0.025x45.08x94.30	0.95	3436	187	Annealed
1	0.025x44.45x92.39	0.86	3436	186	"
1	0.025x44.45x94.61	0.91	3436	185	"
1	0.025x39.37x94.93	0.73	3436	184	"
1	0.025x36.83x91.44	0.73	3436	183	"
1	0.025x44.13x93.34	0.91	3436	181	"
1	0.025x45.08x93.98	0.95	3436	180	"
1	0.025x43.18x90.49	0.86	3436	178	"
1	0.025x45.40x93.03	0.91	3436	182	"
SUB-TOTAL 10 pcs		8.66	3436	39,948.29 Cm^2	
1	0.051x52.07x110.49	2.54	3493	202	Ground
1	0.051x52.07x110.17	2.54	3493	203	"
1	0.051x52.07x110.49	2.59	3493	204	"
1	0.051x52.70x108.58	2.59	3493	205	"
1	0.051x52.07x109.85	2.59	3493	206	"
1	0.051x52.70x110.81	2.59	3493	207	"
1	0.051x52.07x112.39	2.59	3493	208	"
SUB-TOTAL 7 pcs.		18.01	3493	40,412.81 Cm^2	
1	0.051x43.18x98.42	1.91	3510	209	Ground
1	0.051x46.99x111.12	2.31	3510	210	"
1	0.051x46.99x110.81	2.27	3510	211	"
1	0.051x46.99x107.31	2.31	3510	212	"
1	0.051x48.26x105.41	2.22	3510	213	"
1	0.051x44.45x100.01	2.04	3510	214	"
1	0.051x43.18x93.66	1.91	3510	215	"
1	0.051x50.16x99.06	2.27	3510	216	"
SUB-TOTAL 8 pcs		17.24		38,276.04 Cm^2	

TABLE D-3
(CONT'D)

THIRD SHIPMENT

TDNiCr SHEET INVENTORY

Quantity Pcs.	Size (in.)	Wt. #	Heat No.	Serial No.	Finish
1	0.010x15-1/8x37-1/4	1.7	3435	160	Cold Rolled-Annealed
1	0.010x14-7/8x37	1.7	3435	144	"
1	0.010x17-7/8x31	1.7	3435	143	"
1	0.010x18x30-7/8	1.7	3435	142	"
SUB-TOTAL 15 pcs.		24.5	3435	56.7 sq.ft.	
1	0.010x16-3/4x35	1.9	3436	191	Cold Rolled-Annealed
1	0.010x17-3/4x37-1/8	2.1	3436	187	"
1	0.010x17-1/2x36-3/8	1.9	3436	186	"
1	0.010x17-1/2x37-1/4	2.0	3436	185	"
1	0.010x15-1/2x37-3/8	1.6	3436	184	"
1	0.010x14-1/2x36	1.6	3436	183	"
1	0.010x17-3/8x36-3/4	2.0	3436	181	"
1	0.010x17-3/4x37	2.1	3436	180	"
1	0.010x17x35-5/8	1.9	3436	178	"
1	0.010x17-7/8x36-5/8	2.0	3436	182	"
SUB-TOTAL 10 pcs.		19.1	3436	43.0 sq.ft.	
1	0.020x20-1/2x43-1/2	5.6	3493	202	Ground
1	0.020x20-1/2x43-3/8	5.6	3493	203	"
1	0.020x20-1/2x43-1/2	5.7	3493	204	"
1	0.020x20-3/4x42-3/4	5.7	3493	205	"
1	0.020x20-1/2x43-1/4	5.7	3493	206	"
1	0.020x20-3/4x43-5/8	5.7	3493	207	"
1	0.020x20-1/2x44-1/4	5.7	3493	208	"
SUB-TOTAL 7 pcs.		39.7	3493	43.5 sq.ft.	
1	0.020x17x38-3/4	4.2	3510	209	Ground
1	0.020x18-1/2x43-3/4	5.1	3510	210	"
1	0.020x18-1/2x43-5/8	5.0	3510	211	"
1	0.020x18-1/2x42-1/4	5.1	3510	212	"
1	0.020x19x41-1/2	4.9	3510	213	"
1	0.020x17-1/2x39-3/8	4.5	3510	214	"
1	0.020x17x36-7/8	4.2	3510	215	"
1	0.020x19-3/4x39	5.0	3510	216	"
SUB-TOTAL 8 pcs.		38.0	3510	41.2 sq.ft.	

TABLE D-3
(CONT'D)

THIRD SHIPMENT

TDNiCr SHEET INVENTORY

Quantity Pcs.	Size (cm.)	Wt. kg.	Heat No.	Serial No.	Finish
1	0.051x50.48x112.39	2.49	3507	197	Ground
1	0.051x50.16x110.81	2.49	3507	196	"
SUB-TOTAL	2 pcs.	4.98	3507	11,241.26 Cm^2	
1	0.102x50.16x91.44	3.58	3507	195	Ground
1	0.102x52.07x93.03	4.08	3507	194	"
1	0.102x45.72x97.79	3.63	3507	193	"
1	0.102x45.72x91.76	3.45	3507	192	"
SUB-TOTAL	4 pcs.	14.74	3507	18,116.09 Cm^2	
GRAND TOTAL	74 pcs.	94.06		291,901.23 Cm^2	

TABLE D-3
(CONT'D)

THIRD SHIPMENT

TDNiCr SHEET INVENTORY

Quantity Pcs.	Size(in.)	Wt. #	Heat No.	Serial No.	Finish
1	0.020x19-7/8x44-1/4	5.5	3507	197	Ground
1	0.020x19-3/4x43-5/8	5.5	3507	196	"
SUB-TOTAL 2 pcs.		11.0	3507	12.1 sq.ft.	
1	0.040x19-3/4x36	7.9	3507	195	Ground
1	0.040x20-1/2x36-5/8	9.0	3507	194	"
1	0.040x18x38-1/2	8.0	3507	193	"
1	0.040x18x36-1/8	7.6	3507	192	"
SUB-TOTAL 4 pcs.		32.5	3507	19.5 sq.ft.	
GRAND TOTAL 74 pcs.		207.4		314.2 sq.ft.	

TABLE D-4

FOURTH SHIPMENT
TDNiCr SHEET INVENTORY

Quantity Pcs.	Size(cm.)	Wt. kg.	Heat No.	Serial No.	Finish
1	0.025x45.40x71.12	0.73	3473	229	Cold Rolled
1	0.025x45.40x103.50	0.95	3473	230	Annealed
1	0.025x45.40x104.46	1.00	3473	231	"
1	0.025x45.40x100.97	0.95	3473	232	"
SUB-TOTAL	4 pcs.	3.63	3473	17,279.96 Cm^2	
1	0.051x47.62x70.48	1.63	3517	255	Ground
1	0.051x52.07x93.34	2.22	3517	254	"
1	0.051x51.43x68.58	1.54	3517	253	"
1	0.051x52.39x72.07	1.72	3517	252	"
1	0.051x50.80x93.34	2.13	3517	251	"
1	0.051x46.99x90.80	1.91	3517	250	"
1	0.051x52.39x92.07	2.18	3517	249	"
1	0.051x48.26x84.14	1.86	3517	248	"
SUB-TOTAL	8 pcs.	15.20	3517	33,352.18 Cm^2	
1	0.051x45.08x100.01	2.00	3516	263	Ground
1	0.051x50.16x93.98	2.13	3516	262	"
1	0.051x45.72x93.03	1.95	3516	261	"
1	0.051x45.72x95.57	1.91	3516	260	"
1	0.051x45.72x98.74	1.91	3516	259	"
1	0.051x48.89x99.69	2.18	3516	258	"
1	0.051x50.80x98.74	2.18	3516	257	"
1	0.051x50.48x90.80	1.91	3516	256	"
SUB-TOTAL	8 pcs.	16.15	3516	36,789.59 Cm^2	
1	0.051x47.94x106.04	2.13	3499	247	Ground
1	0.051x47.31x107.00	2.27	3499	246	"
1	0.051x46.99x102.23	2.13	3499	245	"
1	0.051x48.89x98.74	2.13	3499	244	"
1	0.051x47.62x103.19	2.18	3499	243	"
1	0.051x49.53x99.38	2.22	3499	242	"
1	0.051x47.31x102.55	2.22	3499	241	"
1	0.051x47.62x102.55	2.04	3499	240	"
SUB-TOTAL	8 pcs.	17.33	3499	39,390.87 Cm^2	

TABLE D-4

FOURTH SHIPMENT
TDNiCr SHEET INVENTORY

Quantity Pcs.	Size (in.)	Wt. #	Heat	Serial No.	Finish
1	0.010x17-7/8x28	1.6	3473	229	Cold Rolled Annealed
1	0.010x17-7/8x40-3/4	2.1	3473	230	" " "
1	0.010x17-7/8x41-1/8	2.2	3473	231	" " "
1	0.010x17-7/8x39-3/4	2.1	3473	232	" " "
SUB-TOTAL 4 pcs		8.0	3473	18.6 sq. ft.	
1	0.020x18-3/4x27-3/4	3.6	3517	255	Ground
1	0.020x20-1/2x36-3/4	4.9	3517	254	"
1	0.020x20-1/4x27	3.4	3517	253	"
1	0.020x20-5/8x28-3/8	3.8	3517	252	"
1	0.020x20x36-3/4	4.7	3517	251	"
1	0.020x18-1/2x35-3/4	4.2	3517	250	"
1	0.020x20-5/8x36-1/4	4.8	3517	249	"
1	0.020x19x33-1/8	4.1	3517	248	"
SUB-TOTAL 8 pcs		33.5	3517	35.9 sq.ft.	
1	0.020x17-3/4x39-3/8	4.4	3516	263	Ground
1	0.020x19-3/4x37	4.7	3516	262	"
1	0.020x18x36-5/8	4.3	3516	261	"
1	0.020x18x37-5/8	4.2	3516	260	"
1	0.020x18x38-7/8	4.2	3516	259	"
1	0.020x19-1/4x39-1/4	4.8	3516	258	"
1	0.020x20x38-7/8	4.8	3516	257	"
1	0.020x19-7/8x35-3/4	4.2	3516	256	"
SUB-TOTAL 8 pcs		35.6	3516	39.6 sq. ft.	
1	0.020x18-7/8x41-3/4	4.7	3499	247	Ground
1	0.020x18-5/8x42-1/8	5.0	3499	246	"
1	0.020x18-1/2x40-1/4	4.7	3499	245	"
1	0.020x19-1/4x38-7/8	4.7	3499	244	"
1	0.020x18-3/4x40-5/8	4.8	3499	243	"
1	0.020x19-1/2x39-1/8	4.9	3499	242	"
1	0.020x18-5/8x40-3/8	4.9	3499	241	"
1	0.020x18-3/4x40-3/8	4.5	3499	240	"
SUB-TOTAL 8 pcs		38.2	3499	42.4 sq. ft.	

TABLE D-4
(CONT'D)

FOURTH SHIPMENT

TDNiCr SHEET INVENTORY

Quantity Pcs.	Size (cm.)	Wt. kg.	Heat No.	Serial No.	Finish
1	0.051x48.26x102.23	2.18	3494	239	Ground
1	0.051x52.07x98.74	2.31	3494	238	"
1	0.051x51.43x98.74	2.22	3494	237	"
1	0.051x51.43x113.03	2.59	3494	236	"
1	0.051x50.80x106.68	2.44	3494	235	"
1	0.051x49.53x114.93	2.54	3494	234	"
1	0.051x51.43x97.15	2.18	3494	233	"
SUB-TOTAL 7 pcs.		16.47	3494	37,068.30 Cm^2	
1	0.076x52.07x106.04	3.58	3508	223	Ground
1	0.076x53.34x73.66	2.54	3508	224	"
1	0.076x52.07x107.95	3.63	3508	225	"
1	0.076x50.80x59.05	1.91	3508	226	"
1	0.076x52.70x101.60	3.49	3508	227	"
1	0.076x53.66x66.04	2.27	3508	228	"
SUB-TOTAL 6 pcs.		17.42	3508	26,941.87 Cm^2	
1	0.076x50.16x86.68	2.77	3501	217	Ground
1	0.076x52.07x93.03	3.13	3501	218	"
1	0.076x49.53x109.85	3.49	3501	219	"
1	0.076x50.16x106.04	3.45	3501	220	"
1	0.076x52.70x91.44	3.22	3501	221	"
1	0.076x52.07x92.71	3.18	3501	222	"
SUB-TOTAL 6 pcs.		19.23	3501	29,636.06 Cm^2	
GRAND TOTAL 47 pcs.		105.39		220,458.82 Cm^2	

TABLE D-4 (CONT'D

FOURTH SHIPMENT
TDNiCr SHEET INVENTORY

Quantity Pcs.	Size(in.)	Wt. #	Heat	Serial No.	Finish
1	0.020x19x40-1/4	4.8	3494	239	Ground
1	0.020x20-1/2x38-7/8	5.1	3494	238	"
1	0.020x20-1/4x38-7/8	4.9	3494	237	"
1	0.020x20-1/4x44-1/2	5.7	3494	236	"
1	0.020x20x42	5.4	3494	235	"
1	0.020x19-1/2x45-1/4	5.6	3494	234	"
1	0.020x20-1/4x38-1/4	4.8	3494	233	"
SUB-TOTAL 7 pcs		36.3	3494	39.9 sq. ft.	
1	0.030x20-1/2x41-3/4	7.9	3508	223	Ground
1	0.030x21x29	5.6	3508	224	"
1	0.030x20-1/2x42-1/2	8.0	3508	225	"
1	0.030x20x23-1/4	4.2	3508	226	"
1	0.030x20-3/4x40	7.7	3508	227	"
1	0.030x21-1/8x26	5.0	3508	228	"
SUB-TOTAL 6 pcs		38.4	3508	29.0 sq. ft.	
1	0.030x19-3/4x34-1/8	6.1	3501	217	Ground
1	0.030x20-1/2x36-5/8	6.9	3501	218	"
1	0.030x19-1/2x43-1/4	7.7	3501	219	"
1	0.030x19-3/4x41-3/4	7.6	3501	220	"
1	0.030x20-3/4x36	7.1	3501	221	"
1	0.030x20-1/2x36-1/2	7.0	3501	222	"
SUB-TOTAL 6 pcs		42.4	3501	31.9 sq. ft.	
GRAND TOTAL 47 pcs		232.4		237.3 sq. ft.	

TABLE D-5

FIFTH SHIPMENT
TDNiCr SHEET INVENTORY

Quantity Pcs.	Size(cm.)	Wt. kg.	Heat No.	Serial No.	Finish
1	0.038x45.72x117.79	1.81	3514	275	Ground
1	0.038x44.45x120.01	1.72	3514	276	"
1	0.038x45.72x119.70	1.91	3514	277	"
1	0.038x49.53x101.28	1.72	3514	278	"
1	0.038x46.35x103.50	1.54	3514	279	"
1	0.038x48.89x105.73	1.68	3514	280	"
1	0.038x48.89x103.19	1.63	3514	281	"
1	0.038x48.89x99.38	1.41	3514	282	"
1	0.038x45.72x114.93	1.68	3514	283	"
1	0.038x49.53x103.82	1.68	3514	306	"
SUB-TOTAL 10 pcs.		16.78	3514	51,468.26 Cm^2	
1	0.038x53.02x101.28	1.77	3511	273	Ground
1	0.038x52.70x100.01	1.72	3511	272	"
1	0.038x54.29x60.32	1.09	3511	271	"
1	0.038x51.75x98.42	1.68	3511	270	"
1	0.038x53.34x92.07	1.68	3511	269	"
1	0.038x53.02x98.11	1.77	3511	268	"
1	0.038x55.24x103.50	1.91	3511	267	"
1	0.038x54.29x102.87	1.77	3511	266	"
1	0.038x54.61x95.25	1.77	3511	265	"
1	0.038x55.56x62.23	1.18	3511	264	"
SUB-TOTAL 10 pcs.		16.33	3511	49,331.49 Cm^2	
1	0.102x55.88x115.57	5.90	3509	293	Ground
1	0.102x54.61x93.34	4.54	3509	292	"
1	0.102x54.61x101.60	4.90	3509	291	"
1	0.102x55.88x92.39	4.49	3509	290	"
SUB-TOTAL 4 pcs.		19.82	3509	22,203.82 Cm^2	
1	0.102x52.07x119.38	5.53	3515	295	Ground
1	0.102x52.07x119.38	5.48	3515	294	"
1	0.102x52.70x103.50	5.22	3515	296	"
1	0.102x52.07x66.99	3.04	3515	297A	"
1	0.102x51.43x25.08	1.09	3515	297B	"
1	0.102x36.83x19.37	0.64	3515	297C	"
SUB-TOTAL 6 pcs.		21.00	3515	23,597.36 Cm^2	

TABLE D-5
FIFTH SHIPMENT
TDNiCr SHEET INVENTORY

Quantity Pcs.	Size (in.)	Wt. #	Heat	Serial No.	Finish
1	0.015x18x46-3/8	4.0	3514	275	Ground
1	0.015x17-1/2x47-1/4	3.8	3514	276	"
1	0.015x18x47-1/8	4.2	3514	277	"
1	0.015x19-1/2x39-7/8	3.8	3514	278	"
1	0.015x18-1/4x40-3/4	3.4	3514	279	"
1	0.015x19-1/4x41-5/8	3.7	3514	280	"
1	0.015x19-1/4x40-5/8	3.6	3514	281	"
1	0.015x19-1/4x39-1/8	3.1	3514	282	"
1	0.015x18x45-1/4	3.7	3514	283	"
1	0.015x19-1/2x40-7/8	3.7	3514	306	"
SUB-TOTAL 10 pcs		37.0	3514	55.4 sq. ft.	
1	0.015x21-7/8x39-7/8	3.9	3511	273	Ground
1	0.015x20-3/4x39-3/8	3.8	3511	272	"
1	0.015x21-3/8x23-3/4	2.4	3511	271	"
1	0.015x20-3/8x38-3/4	3.7	3511	270	"
1	0.015x21x36-1/4	3.7	3511	269	"
1	0.015x20-7/8x38-5/8	3.9	3511	268	"
1	0.015x21-3/4x40-3/4	4.2	3511	267	"
1	0.015x21-3/8x40-1/2	3.9	3511	266	"
1	0.015x21-1/2x37-1/2	3.9	3511	265	"
1	0.015x21-7/8x24-1/2	2.6	3511	264	"
SUB-TOTAL 10 pcs		36.0	3511	53.1 sq. ft.	
1	0.040x22x45-1/2	13.0	3509	293	Ground
1	0.040x21-1/2x36-3/4	10.0	3509	292	"
1	0.040x21-1/2x40	10.8	3509	291	"
1	0.040x22x36-3/8	9.9	3509	290	"
SUB-TOTAL 4 pcs		43.7	3509	23.9 sq. ft.	
1	0.040x20-1/2x47	12.2	3515	295	Ground
1	0.040x20-1/2x47	12.1	3515	294	"
1	0.040x20-3/4x40-3/4	11.5	3515	296	"
1	0.040x20-1/2x26-3/8	6.7	3515	297A	"
1	0.040x20-1/4x9-7/8	2.4	3515	297B	"
1	0.040x14-1/2x7-5/8	1.4	3515	297C	"
SUB-TOTAL 6 pcs		46.3	3515	25.4 sq. ft.	

TABLE D-5
(CONT'D)

FIFTH SHIPMENT
TDNiCr SHEET INVENTORY

Quantity Pcs.	Size (cm.)	Wt. kg.	Heat No.	Serial No.	Finish
1	0.102x44.77x96.84	3.90	3473	201	Ground
SUB-TOTAL	1 pc.	3.90	3473	4,366.44 Cm^2	
1	0.076x53.34x88.90	3.18	3512	286	Ground
SUB-TOTAL	1 pc.	3.18	3512	4,738.05 Cm^2	
1	0.076x46.99x91.44	2.95	3513	307	Ground
1	0.076x46.35x93.98	2.95	3513	301	"
1	0.076x46.35x96.52	3.04	3513	300	"
1	0.076x46.67x95.25	2.99	3513	299	"
SUB-TOTAL	4 pcs.	11.93	3513	17,558.67 Cm^2	
1	0.127x37.46x41.91	1.72	3324	305A	Ground
1	0.127x37.46x41.91	1.72	3324	305B	"
1	0.127x38.10x41.91	1.72	3324	305C	"
SUB-TOTAL	3 pcs.	5.17	3324	4,738.05 Cm^2	
1	0.203x44.45x76.20	6.21	3359	304	Ground
1	0.203x24.76x125.09	5.58	3359	303	"
1	0.203x22.22x110.17	4.90	3359	302	"
SUB-TOTAL	3 pcs.	16.69	3359	8,918.69 Cm^2	
1	0.308x45.72x53.34	6.89	3496	274	Ground
SUB-TOTAL	1 pc.	6.89	3496	2,415.48 Cm^2	
GRAND TOTAL	43 pcs.	121.66		189,336.31 Cm^2	

TABLE II-5 (CONT'D)
FIFTH SHIPMENT
TDNiCr SHEET INVENTORY

Quantity Pcs.	Size (in.)	Wt. #	Heat	Serial No.	Finish
1	0.040x17-5/8x38-1/8	8.6	3473	201	Ground
SUB-TOTAL 1 pc		8.6	3473		4.7 sq. ft.
1	0.030x21x35	7.0	3512	286	Ground
SUB-TOTAL 1 pc		7.0	3512		5.1 sq. ft.
1	0.030x18-1/2x36	6.5	3513	307	Ground
1	0.030x18-1/4x37	6.5	3513	301	"
1	0.030x18-1/4x38	6.7	3513	300	"
1	0.030x18-3/8x37-1/2	6.6	3513	299	"
SUB-TOTAL 4 pcs		26.3	3513		18.9 sq. ft.
1	0.050x14-3/4x16-1/2	3.8	3324	305A	Ground
1	0.050x14-3/4x16-1/2	3.8	3324	305B	"
1	0.050x15x16-1/2	3.8	3324	305C	"
SUB-TOTAL 3 pcs		11.4	3324		5.1 sq. ft.
1	0.080x17-1/2x30	13.7	3359	304	Ground
1	0.080x9-3/4x49-1/4	12.3	3359	303	"
1	0.080x8-3/4x43-3/8	10.8	3359	302	"
SUB-TOTAL 3 pcs		36.8	3359		9.6 sq. ft.
1	0.123x18x21	15.2	3496	274	Ground
SUB-TOTAL 1 pc		15.2	3496		2.6 sq. ft.
GRAND TOTAL - 43 pcs		268.3			203.8 sq. ft.

TABLE D-6

SIXTH SHIPMENT
TDNiCr SHEET INVENTORY

Quantity Pcs.	Size (cm.)	Wt. kg.	Heat No.	Serial No.	Finish
1	0.051x41.91x104.77	1.95	3518	334	Ground
1	0.051x37.46x106.68	1.81	3518	333	"
1	0.051x41.59x105.73	1.95	3518	309	"
1	0.051x41.91x100.65	1.91	3518	308	"
SUB-TOTAL 4 pcs.		7.62	3518	17,001.25 Cm^2	
1	0.076x52.07x121.60	4.31	3622	332	Ground
1	0.076x53.34x106.04	3.72	3622	331	"
1	0.076x51.75x118.11	3.99	3622	330	"
1	0.076x53.34x105.73	3.76	3622	329	"
1	0.076x52.07x109.85	3.72	3622	311	"
1	0.076x54.93x124.78	4.63	3622	310	"
SUB-TOTAL 6 pcs.		24.13	3622	36,325.07 Cm^2	
1	0.076x49.85x117.47	3.81	3638	326	Ground
1	0.076x54.29x106.68	3.90	3638	322	"
1	0.076x53.34x96.52	3.36	3638	321	"
1	0.076x51.43x104.46	3.67	3638	320	"
1	0.076x51.12x115.25	3.86	3638	319	"
1	0.076x48.58x111.76	3.54	3638	318	"
SUB-TOTAL 6 pcs.		22.14	3638	33,445.08 Cm^2	
1	0.076x46.35x112.49	3.49	3639	323	Ground
1	0.076x44.45x103.50	3.04	3639	324	"
1	0.076x53.97x113.03	3.95	3639	325	"
1	0.076x47.62x118.74	3.54	3639	327	"
1	0.076x50.16x107.95	3.45	3639	328	"
1	0.076x41.27x87.31	2.27	3639	335	"
SUB-TOTAL 6 pcs.		19.73	3639	30,286.38 Cm^2	
1	0.076x44.77x115.57	3.31	3626	317	Ground
1	0.076x39.37x125.73	3.27	3626	316	"
1	0.076x48.26x135.89	4.35	3626	315	"
1	0.076x46.35x127.00	3.81	3626	314	"
1	0.076x41.59x128.59	3.27	3626	313	"
1	0.076x43.81x133.98	3.81	3626	312	"
SUB-TOTAL 6 pcs.		21.82	3626	33,909.60 Cm^2	
1	0.203x50.80x105.41	9.48	3455	336	Ground
SUB-TOTAL 1 pc.		9.48	3455	5,388.37 Cm^2	
GRAND TOTAL 29 pcs.		104.89		156,355.75 Cm^2	

TABLE D-6
SIXTH SHIPMENT
TDNiCr SHEET INVENTORY

Quantity Pcs.	Size(in.)	Wt. #	Heat	Serial No.	Finish
1	0.020x16-1/2x41-1/4	4.3	3518	334	Ground
1	0.020x14-3/4x42	4.0	3518	333	"
1	0.020x16-3/8x41-5/8	4.3	3518	309	"
1	0.020x16-1/2x39-5/8	4.2	3518	308	"
SUB-TOTAL 4 pcs.		16.8	3518	18.3 sq.ft.	
1	0.030x20-1/2x47-7/8	9.5	3622	332	Ground
1	0.030x21x41-3/4	8.2	3622	331	"
1	0.030x20-3/8x46-1/2	8.8	3622	330	"
1	0.030x21x41-5/8	8.3	3622	329	"
1	0.030x20-1/2x43-1/4	8.2	3622	311	"
1	0.030x21-5/8x49-1/8	10.2	3622	310	"
SUB-TOTAL 6 pcs.		53.2	3622	39.1 sq.ft.	
1	0.030x19-5/8x46-1/4	8.4	3638	326	Ground
1	0.030x21-3/8x42	8.6	3638	322	"
1	0.030x21x38	7.4	3638	321	"
1	0.030x20-1/4x41-1/8	8.1	3638	320	"
1	0.030x20-1/8x45-3/8	8.5	3638	319	"
1	0.030x19-1/8x44	7.8	3638	318	"
SUB-TOTAL 6 pcs.		48.8	3638	36.0 sq.ft.	
1	0.030x18-1/4x44-1/4	7.7	3639	323	Ground
1	0.030x17-1/2x40-3/4	6.7	3639	324	"
1	0.030x21-1/4x44-1/2	8.7	3639	325	"
1	0.030x18-3/4x46-3/4	7.8	3639	327	"
1	0.030x19-3/4x42-1/2	7.6	3639	328	"
1	0.030x16-1/4x34-3/8	5.0	3639	335	"
SUB-TOTAL 6 pcs.		43.5	3639	32.6 sq.ft.	
1	0.030x17-5/8x45-1/2	7.3	3626	317	Ground
1	0.030x15-1/2x49-1/2	7.2	3626	316	"
1	0.030x19x53-1/2	9.6	3626	315	"
1	0.030x18-1/4x50	8.4	3626	314	"
1	0.030x16-3/8x51-5/8	7.2	3626	313	"
1	0.030x17-1/4x52-3/4	8.4	3626	312	"
SUB-TOTAL 6 pcs		48.1	3626	36.5 sq.ft.	
1	0.080x20x41-1/2	20.9	3455	336	Ground
SUB-TOTAL 1 pc.		20.9	3455	5.8 sq.ft.	
GRAND TOTAL 29 pcs.		231.3		168.3 sq.ft.	

TABLE D-7

SEVENTH SHIPMENT
TDNiCr SHEET INVENTORY

Quantity Pcs.	Size (cm.)	Wt. kg.	Heat No.	Serial No.	Finish
1	0.051x45.72x105.09	2.18	3629	358	Ground
1	0.051x42.54x130.17	2.36	3629	357	Ground
1	0.051x43.18x105.73	1.95	3629	356	Ground
1	0.051x36.83x117.79	1.72	3629	354	Ground
SUB-TOTAL 4 pcs.		8.21	3629	18,952.21 Cm^2	
1	0.051x52.07x88.26	2.09	3636	348	Ground
1	0.051x53.66x89.53	2.00	3636	349	Ground
1	0.051x50.80x93.03	2.00	3636	350	Ground
1	0.051x50.80x94.30	1.95	3636	351	Ground
1	0.051x52.39x86.99	2.04	3636	353	Ground
SUB-TOTAL 5 pcs.		10.07	3636	23,504.46 Cm^2	
1	0.038x51.43x94.93	1.63	3636	367	Ground
1	0.038x45.72x91.44	1.41	3636	368	Ground
1	0.038x53.97x89.22	1.54	3636	369	Ground
SUB-TOTAL 3 pcs.		4.58	3636	13,842.55 Cm^2	
1	0.076x36.83x92.71	2.18	3628	347	Ground
1	0.076x38.73x91.44	2.31	3628	346	Ground
1	0.076x38.73x91.44	2.31	3628	345	Ground
1	0.076x45.72x91.44	2.77	3628	344	Ground
1	0.076x36.83x104.14	2.40	3628	343	Ground
1	0.076x47.62x91.44	2.86	3628	342	Ground
SUB-TOTAL 6 pcs.		14.83	3628	22,854.14 Cm^2	
1	0.102x49.53x113.03	4.99	3623	374	Ground
1	0.102x52.70x109.85	5.22	3623	373	Ground
1	0.102x52.07x117.47	5.48	3623	372	Ground
1	0.102x49.85x115.25	5.08	3623	371	Ground
1	0.102x49.85x113.03	4.94	3623	370	Ground
SUB-TOTAL 5 pcs.		25.72	3623	28,892.83 Cm^2	
1	0.102x47.62x102.23	4.35	3624	341	Ground
1	0.102x53.34x106.04	5.03	3624	340	Ground
1	0.102x49.53x102.87	4.63	3624	339	Ground
1	0.102x43.81x91.76	3.49	3624	338	Ground
1	0.102x43.18x100.97	3.72	3624	337	Ground
SUB-TOTAL 5 pcs.		21.23	3624	23,968.97 Cm^2	
GRAND TOTAL 28 pcs.		84.59		132,015.16 Cm^2	

TABLE D-7

SEVENTH SHIPMENT TDNiCr SHEET INVENTORY

Quantity Pcs.	Size (in.)	Wt. #	Heat	Serial No.	Finish
1	0.020x18x41-3/8	4.8	3629	358	Ground
1	0.020x16-3/4x51-1/4	5.2	3629	357	Ground
1	0.020x17x41-5/8	4.3	3629	356	Ground
1	0.020x13-1/2x46-3/8	3.8	3629	354	Ground
Sub-Total	4 pcs	18.1	3629	20.4 sq.ft.	
1	0.020x20-1/2x34-3/4	4.6	3636	348	Ground
1	0.020x21-1/8x35-1/4	4.4	3636	349	Ground
1	0.020x20x36-5/8	4.4	3636	350	Ground
1	0.020x20x37-1/8	4.3	3636	351	Ground
1	0.020x20-5/8x34-1/4	4.5	3636	353	Ground
Sub-Total	5 pcs	22.2	3636	25.3 sq.ft.	
1	0.015 x20-1/4x37-3/8	3.6	3636	367	Ground
1	0.015 x18x36	3.1	3636	368	Ground
1	0.015 x21-1/4x35-1/8	3.4	3636	369	Ground
Sub-Total	3 pcs	10.1	3636	14.9 sq.ft.	
1	0.030x14-1/2x36-1/2	4.8	3628	347	Ground
1	0.030x15-1/4x36	5.1	3628	346	Ground
1	0.030x15-1/4x36	5.1	3628	345	Ground
1	0.030x18x36	6.1	3628	344	Ground
1	0.030x14-1/2x41	5.3	3628	343	Ground
1	0.030x18-3/4x36	6.3	3628	342	Ground
Sub-Total	6 pcs	32.7	3628	24.6 sq.ft.	
1	0.040x19-1/2x44-1/2	11.0	3623	374	Ground
1	0.040x20-3/4x43-1/4	11.5	3623	373	Ground
1	0.040x20-1/2x46-1/4	12.1	3623	372	Ground
1	0.040x19-5/8x45-3/8	11.2	3623	371	Ground
1	0.040x19-5/8x44-1/2	10.9	3623	370	Ground
Sub-Total	5 pcs	56.7	3623	31.1 sq.ft.	
1	0.040x18-3/4x40-1/4	9.6	3624	341	Ground
1	0.040x21x41-3/4	11.1	3624	340	Ground
1	0.040x19-1/2x40-1/2	10.2	3624	339	Ground
1	0.040x17-1/4x36-1/8	7.7	3624	338	Ground
1	0.040x17x39-3/4	8.2	3624	337	Ground
Sub-Total	5 pcs	46.8	3624	25.8 sq.ft.	
GRAND TOTAL	28 pcs	186.6		142.1 sq.ft.	

TABLE D-8

EIGHTH SHIPMENT
TDNiCr SHEET INVENTORY

Quantity Pcs.	Size (cm.)	Wt. kg.	Heat No.	Serial No.	Finish
1	0.051x45.72x91.44	1.77	3640	378	Ground
1	0.051x48.26x94.93	1.95	3640	377	"
1	0.051x44.45x91.76	1.81	3640	376	"
1	0.051x45.08x93.03	1.86	3640	375	"
1	0.051x42.54x80.96	1.41	3640	392	"
1	0.051x47.31x84.77	1.72	3640	393	"
1	0.076x46.99x85.72	1.72	3640	394	"
1	0.051x47.31x86.36	1.77	3640	395	"
1	0.051x46.35x96.52	1.86	3640	396	"
1	0.038x43.18x85.09	1.27	3640	425	"
SUB-TOTAL 10 pcs.		17.15	3640	40,784.42 Cm^2	
1	0.051x47.94x93.34	1.95	3630	391	Ground
1	0.051x48.26x92.39	1.91	3630	387	"
1	0.051x53.34x93.34	2.04	3630	385	"
1	0.051x45.72x92.39	1.68	3630	384	"
1	0.051x55.88x95.25	1.63	3630	407	"
1	0.051x48.26x93.66	1.45	3630	406	"
1	0.038x53.34x85.72	1.50	3630	390	"
1	0.038x38.73x90.80	1.09	3630	389	"
1	0.038x43.18x90.17	1.22	3630	388	"
1	0.038x48.26x87.63	1.36	3630	386	"
SUB-TOTAL 10 pcs.		15.83	3630	44,221.83 Cm^2	
1	0.025x48.58x127.32	1.36	3632	423	
1	0.025x47.94x91.76	1.00	3632	422	
1	0.025x46.04x91.76	1.04	3632	419	
1	0.025x46.99x71.75	0.82	3632	413	
SUB-TOTAL 4 pcs.		4.13	3632	18,208.99 Cm^2	
1	0.025x45.72x84.45	0.82	3634	383	
1	0.025x48.26x89.53	0.86	3634	382	
1	0.025x50.16x86.99	0.91	3634	381	
1	0.025x50.16x94.93	1.13	3634	380	
1	0.025x49.53x91.76	1.13	3634	379	
1	0.025x50.80x100.01	1.13	3634	397	Ground
1	0.025x49.85x92.07	1.09	3634	398	"
1	0.025x49.85x90.80	1.04	3634	399	"
1	0.025x50.48x95.25	1.04	3634	410	"
1	0.025x49.53x92.71	1.04	3634	424	"
SUB-TOTAL 10 pcs.		10.21	3634	45,429.57 Cm^2	

TABLE D-8

EIGHTH SHIPMENT
TDNiCr SHEET INVENTORY

Quantity Pcs.	Size (in)	Wt. #	Heat	Serial No.	Finish
1	0.020x18x36	3.9	3640	378	Ground
1	0.020x19x37-3/8	4.3	3640	377	"
1	0.020x17-1/2x36-1/8	4.0	3640	376	"
1	0.020x17-3/4x36-5/8	4.1	3640	375	"
1	0.020x16-3/4x31-7/8	3.1	3640	392	"
1	0.020x18-5/8x33-3/8	3.8	3640	393	"
1	0.030x18-1/2x33-3/4	3.8	3640	394	"
1	0.020x18-5/8x34	3.9	3640	395	"
1	0.020x18-1/4x38	4.1	3640	396	"
1	0.015x17x33-1/2	2.8	3640	425	"
SUB-TOTAL 10 pcs.		37.8	3640	43.9 sq.ft.	
1	0.020x18-7/8x36-3/4	4.3	3630	391	Ground
1	0.020x19x36-3/8	4.2	3630	387	"
1	0.020x21x36-3/4	4.5	3630	385	"
1	0.020x18x36-3/8	3.7	3630	384	"
1	0.020x22x37-1/2	3.6	3630	407	"
1	0.020x19x36-7/8	3.2	3630	406	"
1	0.015x21x33-3/4	3.3	3630	390	"
1	0.015x15-1/4x35-3/4	2.4	3630	389	"
1	0.015x17x35-1/2	2.7	3630	388	"
1	0.015x19x34-1/2	3.0	3630	386	"
SUB-TOTAL 10 pcs		34.9	3630	47.6 sq.ft.	
1	0.010x19-1/8x50-1/8	3.0	3632	423	
1	0.010x18-7/8x36-1/8	2.2	3632	422	
1	0.010x18-1/8x36-1/8	2.1	3632	419	
1	0.010x18-1/2x28-1/4	1.8	3632	413	
SUB-TOTAL 4 pcs		9.1	3632	19.6 sq.ft.	
1	0.010x18x33-1/4	1.8	3634	383	
1	0.010x19x35-1/4	1.9	3634	382	
1	0.010x19-3/4x34-1/4	2.0	3634	381	
1	0.010x19-3/4x37-3/8	2.5	3634	380	
1	0.010x19-1/2x36-1/8	2.5	3634	379	
1	0.010x20x39-3/8	2.5	3634	397	Ground
1	0.010x19-5/8x36-1/4	2.4	3634	398	"
1	0.010x19-5/8x35-3/4	2.3	3634	399	"
1	0.010x19-7/8x37-1/2	2.3	3634	410	"
1	0.010x19-1/2x36-1/2	2.3	3634	424	"
SUB-TOTAL 10 pcs		22.5	3634	48.9 sq.ft.	

TABLE D-8
(CONT'D)

EIGHTH SHIPMENT TDNiCr SHEET INVENTORY

Quantity Pcs.	Size (cm.)	Wt. kg.	Heat No.	Serial No.	Finish
1	0.025x48.58x91.76	0.95	3520	420	
1	0.025x55.24x154.00	1.91	3520	431	
1	0.025x54.61x151.76	1.91	3520	430	
1	0.025x46.04x91.76	0.91	3520	432	
1	0.025x54.61x152.72	1.81	3520	433	
1	0.025x51.12x91.76	1.00	3520	440	
SUB-TOTAL 6 pcs.		8.48	3520	35,303.14 Cm^2	
1	0.025x61.28x152.72	2.09	3523	437	
1	0.025x61.28x253.05	3.49	3523	435	
1	0.025x46.04x125.73	1.27	3523	429	
1	0.025x53.08x128.59	1.50	3523	428	
1	0.025x52.70x111.12	1.45	3523	427	
SUB-TOTAL 5 pcs.		9.80	3523	42,735.38 Cm^2	
1	0.025x47.62x130.81	1.45	3526	459	Cold Rolled-Anneal
1	0.025x47.62x129.54	1.36	3526	460	"
1	0.025x47.62x107.63	1.18	3526	461	"
1	0.025x46.99x132.40	1.50	3526	462	"
1	0.025x48.26x148.91	1.63	3526	463	"
1	0.025x45.72x131.13	1.36	3526	464	"
1	0.025x48.26x153.67	1.63	3526	465	"
1	0.025x49.53x142.87	1.68	3526	466	"
1	0.025x50.16x147.95	1.68	3526	467	"
1	0.025x47.62x137.48	1.45	3526	468	"
1	0.025x49.53x145.73	1.63	3526	469	"
1	0.025x46.99x137.16	1.36	3526	470	"
SUB-TOTAL 12 pcs.		17.92	3526	79,060.45 Cm^2	
1	0.025x48.26x132.40	1.41	3635	445	Cold Rolled-Anneal
1	0.025x47.62x130.17	1.32	3635	446	"
1	0.025x48.26x130.17	1.41	3635	447	"
1	0.025x46.99x175.89	1.77	3635	448	"
1	0.025x48.26x121.28	1.32	3635	449	"
1	0.025x49.53x120.01	1.22	3635	450	"
1	0.025x49.53x112.71	1.22	3635	451	"
1	0.025x48.26x133.03	1.41	3635	452	"
1	0.025x48.89x109.54	1.22	3635	453	"
1	0.025x46.35x178.73	1.63	3635	454	"
1	0.025x46.99x179.70	1.72	3635	455	"
SUB-TOTAL 11 pcs.		15.65	3635	72,928.86 Cm^2	

TABLE D-8
(CONT'D)

EIGHTH SHIPMENT TDNiCr SHEET INVENTORY

Quantity Pcs.	Size(in.)	Wt. #	Heat	Serial No.	Finish
1	0.010x19-1/8x36-1/8	2.1	3520	420	
1	0.010x21-3/4x60-5/8	4.2	3520	431	
1	0.010x21-1/2x59-3/4	4.2	3520	430	
1	0.010x18-1/8x36-1/8	2.0	3520	432	
1	0.010x21-1/2x60-1/8	4.0	3520	433	
1	0.010x20-1/8x36-1/8	2.2	3520	440	
SUB-TOTAL 6 pcs		18.7	3520	38.0 sq.ft.	
1	0.010x24-1/8x60-1/8	4.6	3523	437	
1	0.010x24-1/8x99-5/8	7.7	3523	435	
1	0.010x18-1/8x49-1/2	2.8	3523	429	
1	0.010x20-7/8x50-5/8	3.3	3523	428	
1	0.010x20-3/4x43-3/4	3.2	3523	427	
SUB-TOTAL 5 pcs		21.6	3523	46.0 sq.ft.	
1	0.010x18-3/4x51-1/2	3.2	3526	459	Cold Rolled-Anneal
1	0.010x18-3/4x51	3.0	3526	460	"
1	0.010x18-3/4x42-3/8	2.6	3526	461	"
1	0.010x18-1/2x52-1/8	3.3	3526	462	"
1	0.010x19x58-5/8	3.6	3526	463	"
1	0.010x18x51-5/8	3.0	3526	464	"
1	0.010x19x60-1/2	3.6	3526	465	"
1	0.010x19-1/2x56-1/4	3.7	3526	466	"
1	0.010x19-3/4x58-1/4	3.7	3526	467	"
1	0.010x18-3/4x54-1/8	3.2	3526	468	"
1	0.010x19-1/2x57-3/8	3.6	3526	469	"
1	0.010x18-1/2x54	3.0	3526	470	"
SUB-TOTAL 12 pcs		39.5	3526	85.1 sq.ft.	
1	0.010x19x52-1/8	3.1	3635	445	Cold Rolled-Anneal
1	0.010x18-3/4x51-1/4	2.9	3635	446	"
1	0.010x19x51-1/4	3.1	3635	447	"
1	0.010x18-1/2x69-1/4	3.9	3635	448	"
1	0.010x19x47-3/4	2.9	3635	449	"
1	0.010x19-1/2x47-1/4	2.7	3635	450	"
1	0.010x19-1/2x44-3/8	2.7	3635	451	"
1	0.010x19x52-3/8	3.1	3635	452	"
1	0.010x19-1/4x43-1/8	2.7	3635	453	"
1	0.010x18-1/4x70-1/4	3.6	3635	454	"
1	0.010x18-1/2x70-3/4	3.8	3635	455	"
SUB-TOTAL 11 pcs		34.5	3635	78.5 sq.ft.	

TABLE D-8
(CONT'D)

EIGHTH SHIPMENT TDNiCr SHEET INVENTORY

Quantity Pcs.	Size (cm.)	Wt. kg.	Heat No.	Serial No.	Finish
1	0.025x45.72x114.30	1.22	3637	457	Cold Rolled-Anneal
1	0.025x45.72x120.01	1.27	3637	458	"
SUB-TOTAL 2 pcs.		2.49	3637	10,683.85 Cm^2	
1	0.025x48.26x151.13	1.68	3522	456	Cold Rolled-Anneal
SUB-TOTAL 1 pc.		1.68	3522	7,339.34 Cm^2	
1	0.254x45.72x116.84	11.93	3453	471	Ground
SUB-TOTAL 1 pc.		11.93	3453	5,388.37 Cm^2	
1	0.025x46.99x184.78	1.72	3694	479	Cold Rolled-A Anneal
1	0.025x46.35x181.61	1.77	3694	478	"
1	0.025x46.35x112.71	1.13	3694	476A	"
1	0.025x46.99x104.46	1.00	3694	477A	"
1	0.025x46.35x59.05	0.64	3694	476B	"
1	0.025x46.99x68.58	0.68	3694	477B	"
1	0.025x46.35x181.93	1.86	3694	475	"
1	0.025x46.67x173.35	1.72	3694	474	"
1	0.025x46.99x170.81	1.68	3694	473	"
SUB-TOTAL 9 pcs.		12.20	3694	57,785.67 Cm^2	
1	0.025x44.77x146.68	1.41	3627	487	Cold Rolled-Anneal
1	0.025x44.45x151.76	1.54	3627	488	"
1	0.025x42.54x132.08	1.22	3627	489	"
1	0.025x43.18x131.44	1.27	3627	490	"
SUB-TOTAL 4 pcs.		5.44	3627	24,805.10 Cm^2	
1	0.025x46.35x181.61	1.77	3525	493	Cold Rolled Anneal
SUB-TOTAL 1 pc.		1.77	3525	8,454.17 Cm^2	
1	0.038x44.77x150.49	2.22	3519	443*	Ground
1	0.038x45.08x153.67	2.27	3519	444*	"
1	0.038x45.72x103.50	1.41	3519	494	"
1	0.038x49.53x154.30	2.59	3519	495	"
SUB-TOTAL 4 pcs.		8.48	3519	26,012.84 Cm^2	
GRAND TOTAL 90 pcs.		142.87		519,141.96 Cm^2	

*Unrecrystallized

TABLE D-8
(CONT'D)

EIGHTH SHIPMENT TDNiCr SHEET INVENTORY

Quantity Pcs.	Size(in.)	Wt. #	Heat	Serial No.	Finish
1	0.010x18x45	2.7	3637	457	Cold Rolled-Anneal
1	0.010x18x47-1/4	2.8	3637	458	"
SUB-TOTAL 2 pcs		5.5	3637	11.5 sq.ft.	
1	0.010x19x59-1/2	3.7	3522	456	Cold Rolled-Anneal
SUB-TOTAL 1 pc		3.7	3522	7.9 sq.ft.	
1	0.100x18x46	26.3	3453	471	Ground
SUB-TOTAL 1 pc		26.3	3453	5.8 sq.ft.	
1	0.010x18-1/2x72-3/4	3.8	3694	479	Cold Rolled-Anneal
1	0.010x18-1/4x71-1/2	3.9	3694	478	"
1	0.010x18-1/4x44-3/8	2.5	3694	476-A	"
1	0.010x18-1/2x41-1/8	2.2	3694	477-A	"
1	0.010x18-1/4x23-1/4	1.4	3694	476-B	"
1	0.010x18-1/2x27	1.5	3694	477-B	"
1	0.010x18-1/4x71-5/8	4.1	3694	475	"
1	0.010x18-3/8x68-1/4	3.8	3694	474	"
1	0.010x18-1/2x67-1/4	3.7	3694	473	"
SUB-TOTAL 9 pcs		26.9	3694	62.2 sq.ft.	
1	0.010x17-5/8x57-3/4	3.1	3627	487	Cold Rolled-Anneal
1	0.010x17-1/2x59-3/4	3.4	3627	488	"
1	0.010x16-3/4x52	2.7	3627	489	"
1	0.010x17x51-3/4	2.8	3627	490	"
SUB-TOTAL 4 pcs		12.0	3627	26.7 sq.ft.	
1	0.010x18-1/4x71-1/2	3.9	3525	493	Cold Rolled-Anneal
SUB-TOTAL 1 pc		3.9	3525	9.1 sq.ft.	
1	0.015x17-5/8x59-1/4	4.9	3519	443*	Ground
1	0.015x17-3/4x60-1/2	5.0	3519	444*	"
1	0.015x18x40-3/4	3.1	3519	494	"
1	0.015x19-1/2x60-3/4	5.7	3519	495	"
SUB-TOTAL 4 pcs		18.7	3519	28.0 sq.ft.	
GRAND TOTAL 90 pcs		315.0		558.8 sq.ft.	

*Unrecrystallized

PRECEDING PAGE BLANK NOT FILMED

APPENDIX E

NEW FACILITIES

WARM ROLLING OVEN

A furnace was built by Trent, Inc., Philadelphia, Pa. to provide a facility for heating scaled-up TDNiCr sheet in the temperature range of 538°C(1000°F) to 871°C(1600°F) for isothermal rolling. It was purchased and installed under NASA Contract NAS 3-13490.

The furnace, shown in Figure E-1, consists of a carbon steel outer casing with carbon steel end plates and internal reinforcing angles. The furnace insulation consists of brick, backed with Careytemp slab type insulation. The heating elements are Trent "Folded & Formed" type Tophet 30 ribbon mounted in ceramic element retainers which are in turn keyed to the brick chamber liner. These elements are divided into three controllable zones with their power leads fastened to terminal blocks inside of metal enclosures located on both sidewalls of the furnace.

The furnace contains a reinforced type 330 stainless steel work load muffle complete with shelf supports. This muffle rests in a stand which has been fabricated from type 330 stainless steel structural angles. The air recirculation system is set up by three motors mounted to the outer casing on one side of the furnace. Each motor drives a 60.96 cm.(24 in.) diameter type 330 stainless steel fan through a sheave and belt arrangement. These fans force air across the top and bottom of the muffle, and around the heating elements. The fans then draw the air into one side of the muffle, across the work load, and into the fan chamber to be recirculated again.

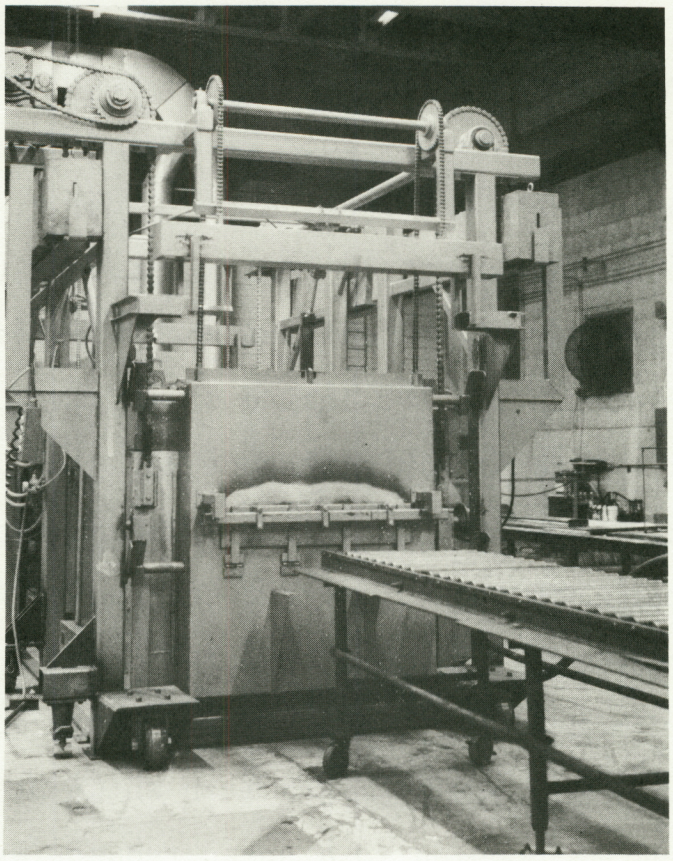


FIGURE E-1

WARM ROLLING OVEN

The furnace has two main doors, one at each end. Each door is counterweighted and operated by an air cylinder which is controlled by a solenoid valve. These doors are moved away from the furnace when it is repositioned to a new loading level. Each main door contains a small sub-door through which the work passes to enter the furnace. These sub-doors are manually operated by a door handle mechanism from one side of the furnace.

This furnace is complete with a lift off top and a removable throat at one end for maintenance purposes.

The furnace is mounted inside of a framework, for raising and lowering, to attain different work levels in the furnace. This framework is constructed of square and rectangular mechanical carbon steel tubing and is mounted on casters for mobility. The furnace is counterweighted and driven up and down by an electric motor. The motor is a double ended type, one end being coupled to a plugging switch which prevents coasting. The other end is coupled to a speed reducer which in turn is connected to one of the drive shafts through a chain and sprocket combination. This shaft is connected to the other drive shaft through a pair of miter boxes. The furnace is hung from one side of each shaft and the counterweight from the other side of each shaft by means of a roller chain. The system is complete with a torque limiter. This drive system will raise or lower the furnace at a speed of 149.86 cm.(59.0 in.) per minute.

The counterweights for the furnace weight approximately 90.7 kg.(200 lbs.) each and have a lifting eye for easy

installation. Since the center of gravity of the furnace is not on the furnace centerline, it is necessary to mount more counterweights on the side of the furnace with the fan motors. Counterweight guards for both the above weights and the door counterweights are welded to the framework. Also mounted on the framework are the air cylinders bearings, sprockets and chain, and counterweights for the main doors.

Mounted on one side of the framework is the control cubicle which contains the following:

- Three Honeywell Pyrovane controllers for use with each of the heat zones.
- One Honeywell Protectovane excess temperature cutout.
- A Westinghouse circuit breaker.
- Three manual motor starters for the motors in each heat zone.
- Three on/off switches with pilot lights for use with the three heat zones.
- A control circuit transformer.
- All necessary relays and fuses.

Attached to the cubicle is a four unit push button station on a retractable cord. From this station, the operator can open or close the main doors and raise or lower the furnace. These motions are interlocked and controlled by limit switches.

The furnace is located adjacent to a rollout table which is adjacent to a two-high United Mill. Figure E-2 shows a canned TDNiCr sheet being extracted from the furnace. Sub-

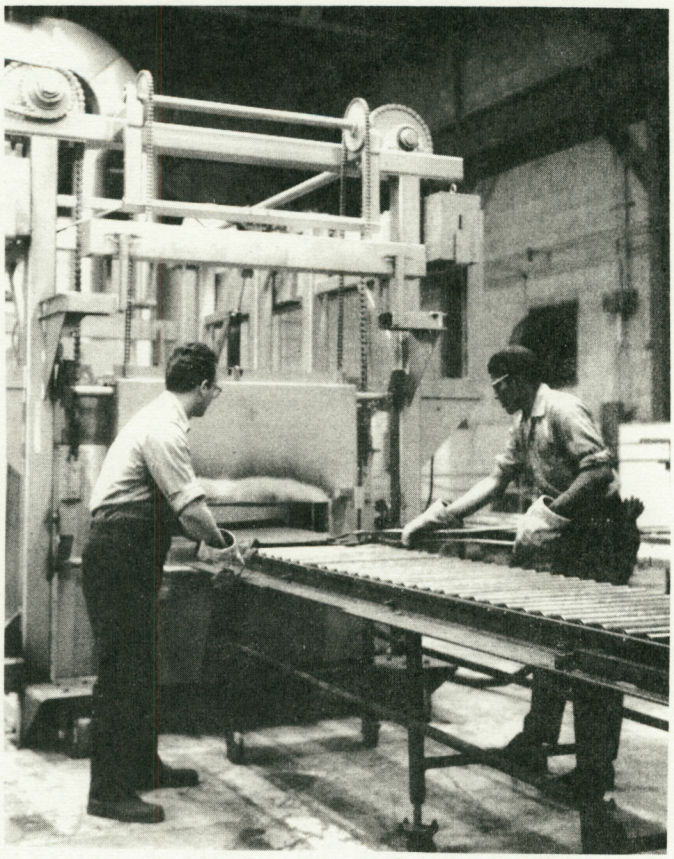


FIGURE E-2

EXTRACTION OF CANNED TDNiCr SHEET
FROM WARM ROLLING OVEN

sequently, the work piece is subjected directly to a reversible rolling mill. After one pass, the mill is reversed and the piece subjected to a second pass and returned to the oven. This operation is then repeated for each shelf in the oven. As a result, a more uniform rolling temperature may be maintained and greater efficiency of personnel realized.

As mentioned in the furnace description, it is mounted on casters allowing mobility so that the furnace may be relocated and used in conjunction with equipment other than the United Mill.

SINTER CONSOLIDATION FURNACE

The furnace shown in Figure E-3 was designed, built and installed under NASA Contract NAS 3-13490.

The furnace, built by Pereny, is an atmosphere sealed unit having a uniformly heated zone 60.96 cm. wide, 45.72 cm. high and 91.44 cm. deep(24 x 18 x 36 in.). The heating elements of the furnace are silicon carbide and produce temperatures up to 1538°C(2800°F) dependent upon the atmosphere to which they may be subjected during use.

The primary purpose of this furnace is to combine the sintering, consolidation and hot rolling breakdown operations into one step and thus eliminate the necessity of cooling down after sintering and recanning plus reheating prior to roll consolidation and hot roll breakdown of dispersion modified type materials.

In addition, this furnace may be utilized for heat treating of conventional TDNiCr sheet as well as developmental alloys at temperatures limited by the silicon carbide elements and atmosphere employed.

Figure E-4 is a photograph taken from the rear side of the sinter-consolidation furnace showing the gas control panel and associated plumbing utilized for gas flow through the canned TDNiCr compacts during the sintering-hot rolling preheat operations. Figure E-5 shows typical TDNiCr canned compacts ready for insertion in the sinter-consolidation furnace. Figure E-6 shows three TDNiCr canned compacts placed in the sinter-consolidation furnace in preparation for the sinter-roll consolidation heat up cycle.

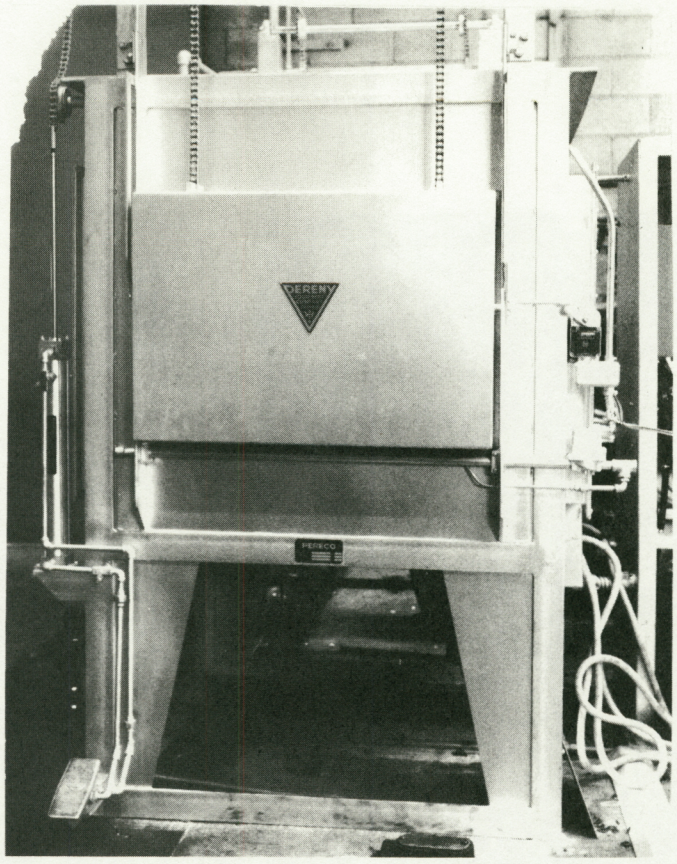


FIGURE E-3

SINTER-CONSOLIDATION FURNACE

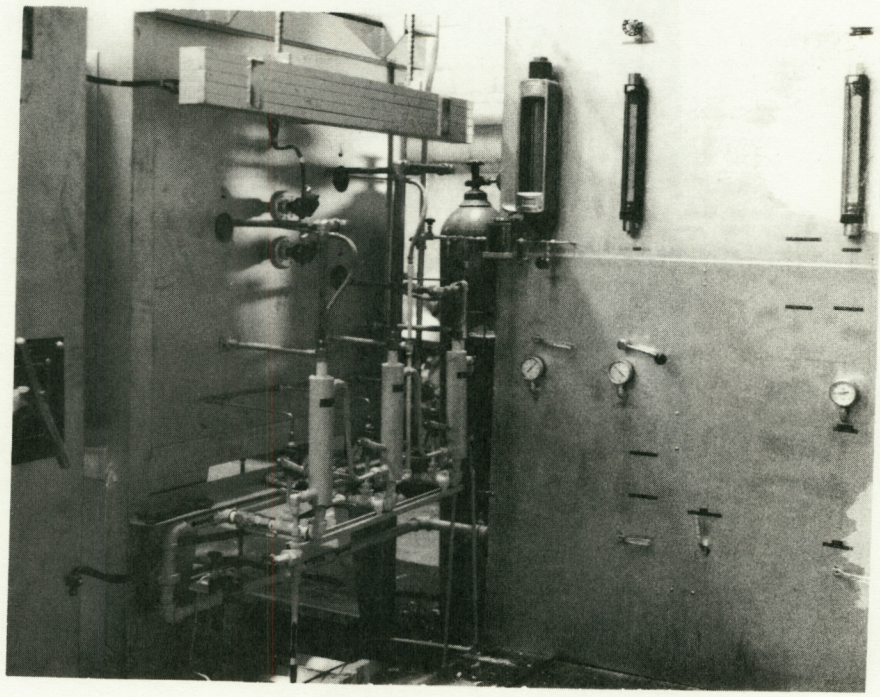


FIGURE E-4

SINTER-CONSOLIDATION FURNACE

GAS CONTROL PANEL AND ASSOCIATED PLUMBING

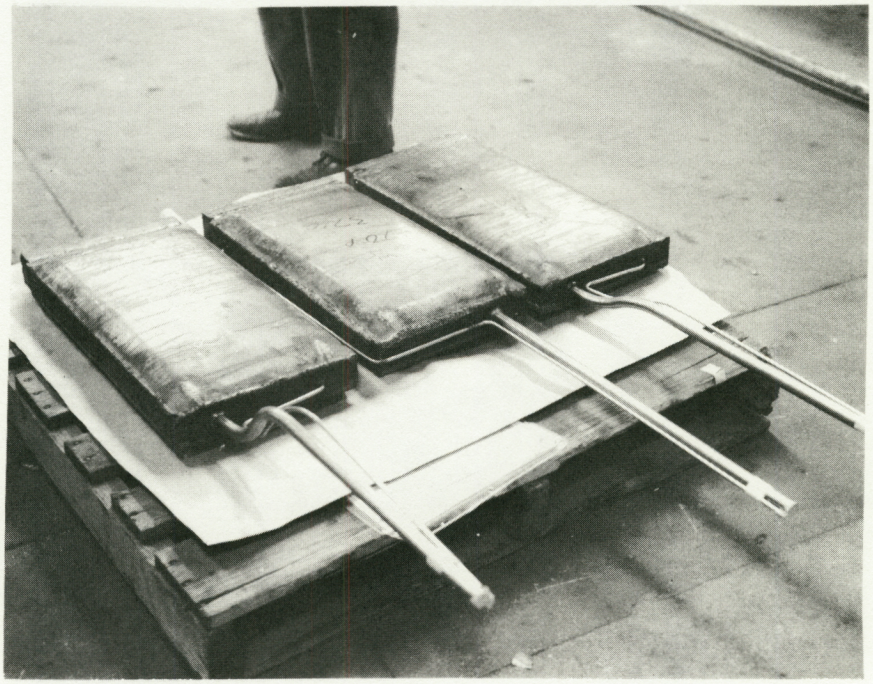


FIGURE E-5

TDNiCr COMPACTS CANNED FOR
SINTER-CONSOLIDATION CYCLE

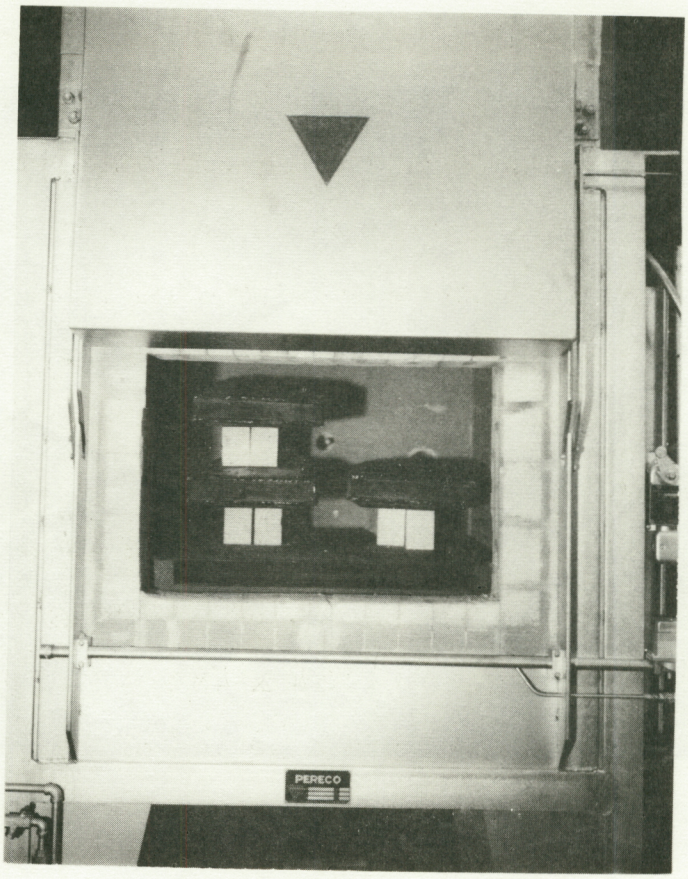


FIGURE E-6

TDNiCr CANNED COMPACTS POSITIONED

IN SINTER-CONSOLIDATION FURNACE

CHEMICAL CONDITIONING AREA

Fansteel designed, built and installed an updated in-process and final product chemical conditioning area for specific use on dispersion modified materials.

This facility consists of six in-line tanks along with the necessary ventilation to accommodate descaling of nickel and nickel alloys, bright dip acid solution, mild hydrochloric acid - ferric chloride - water solution for removal of iron traces, resulting from processing cans, and appropriate cold and hot water rinse tanks. These tanks are of a size to accommodate sheet and plate up to 91.44 cm. wide and 274.32 cm. in length (36 x 108 in.).

In addition, facilities are available for the pickle decanning of either forged slabs and shapes or plates up to 60.96 x 121.92 x 101.60 cm.(24 x 48 x 40 in.). Also available is a ventilation system and a series of temporary trough type tanks which will accommodate tubing, rods and bars up to lengths of 304.80 cm.(120 in.).

A typical view of some of the tanks and associated handling equipment in this cleaning facility are shown in Figure E-7.

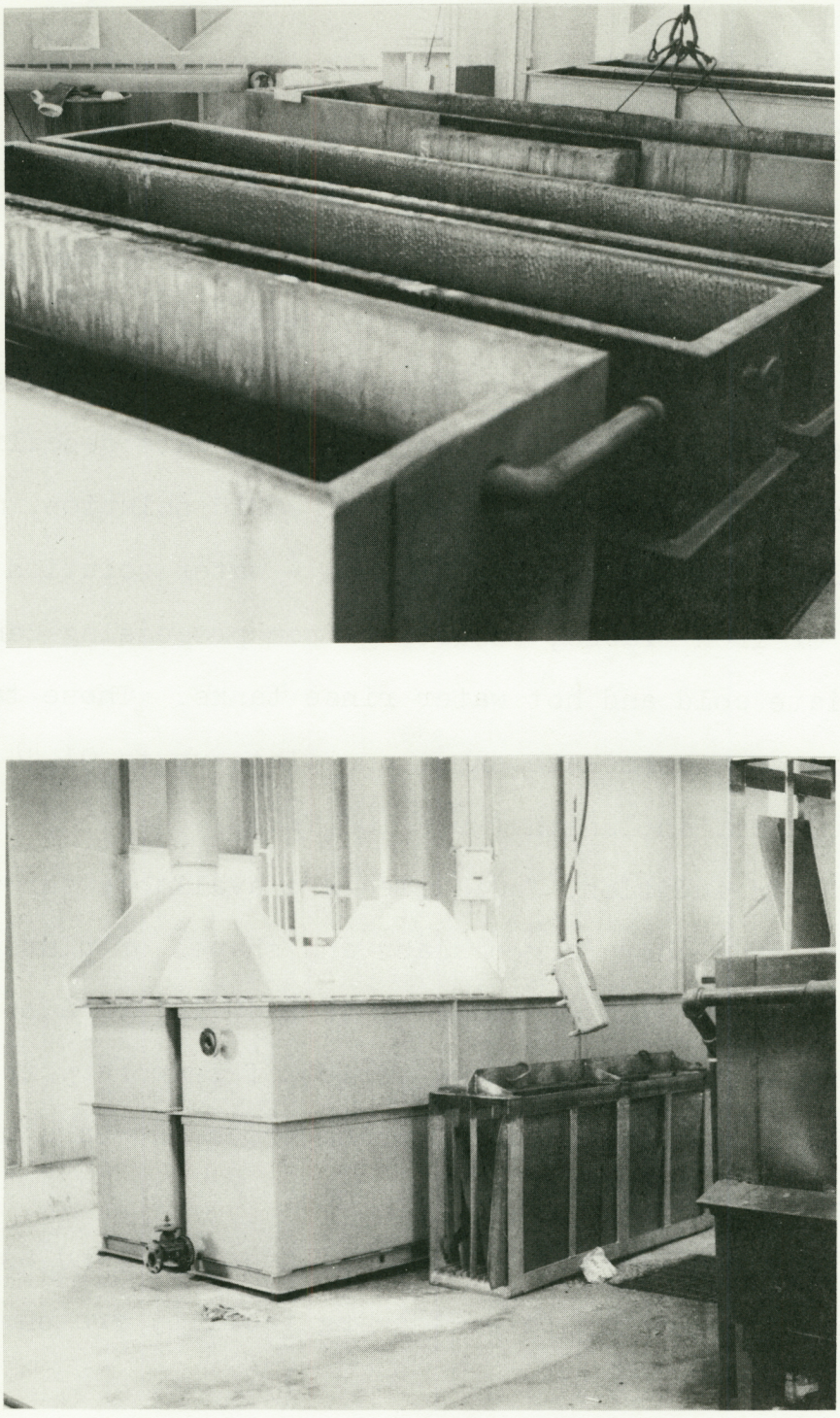


FIGURE E-7

TYPICAL VIEW OF TANKS AND ASSOCIATED HANDLING EQUIPMENT
IN FANSTEEL DISPERSION MODIFIED MATERIALS CLEANING FACILITY

APPENDIX F

CYCLIC OXIDATION DATA

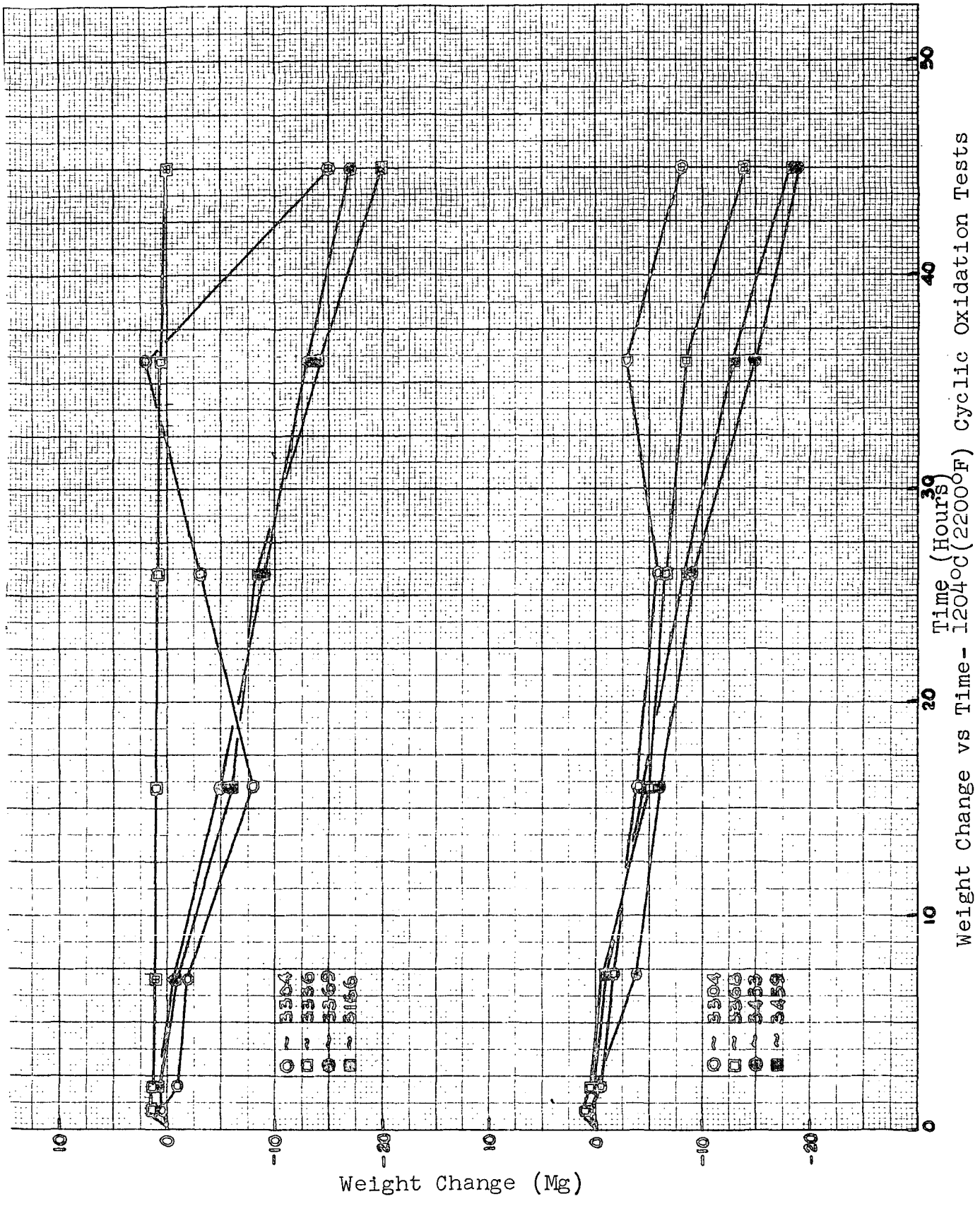


FIGURE F-1 - OXIDATION BEHAVIOR OF EXPERIMENTAL TDNiCr BASE ALLOYS

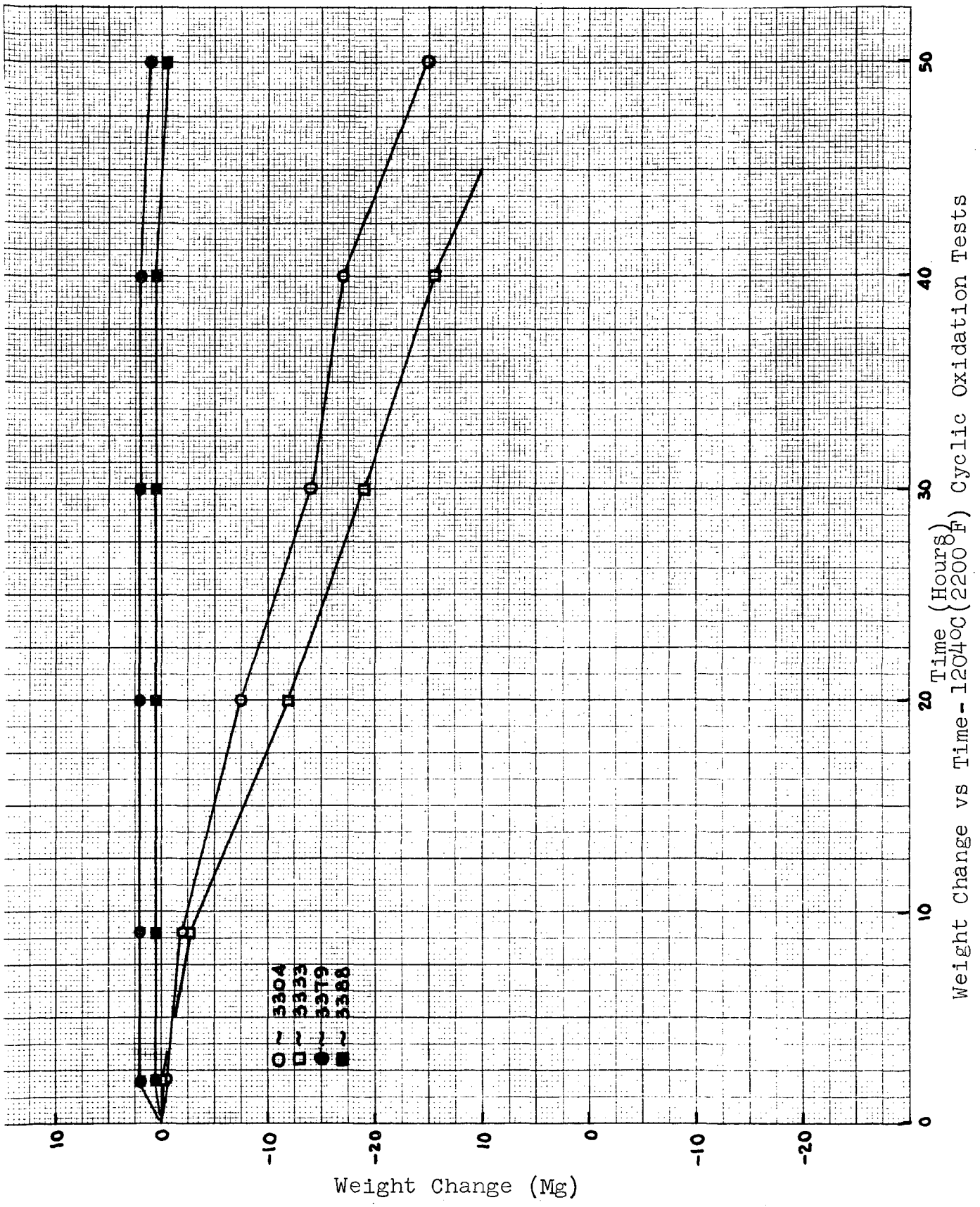


FIGURE F-2 - OXIDATION BEHAVIOR OF EXPERIMENTAL TDNiCr BASE ALLOYS

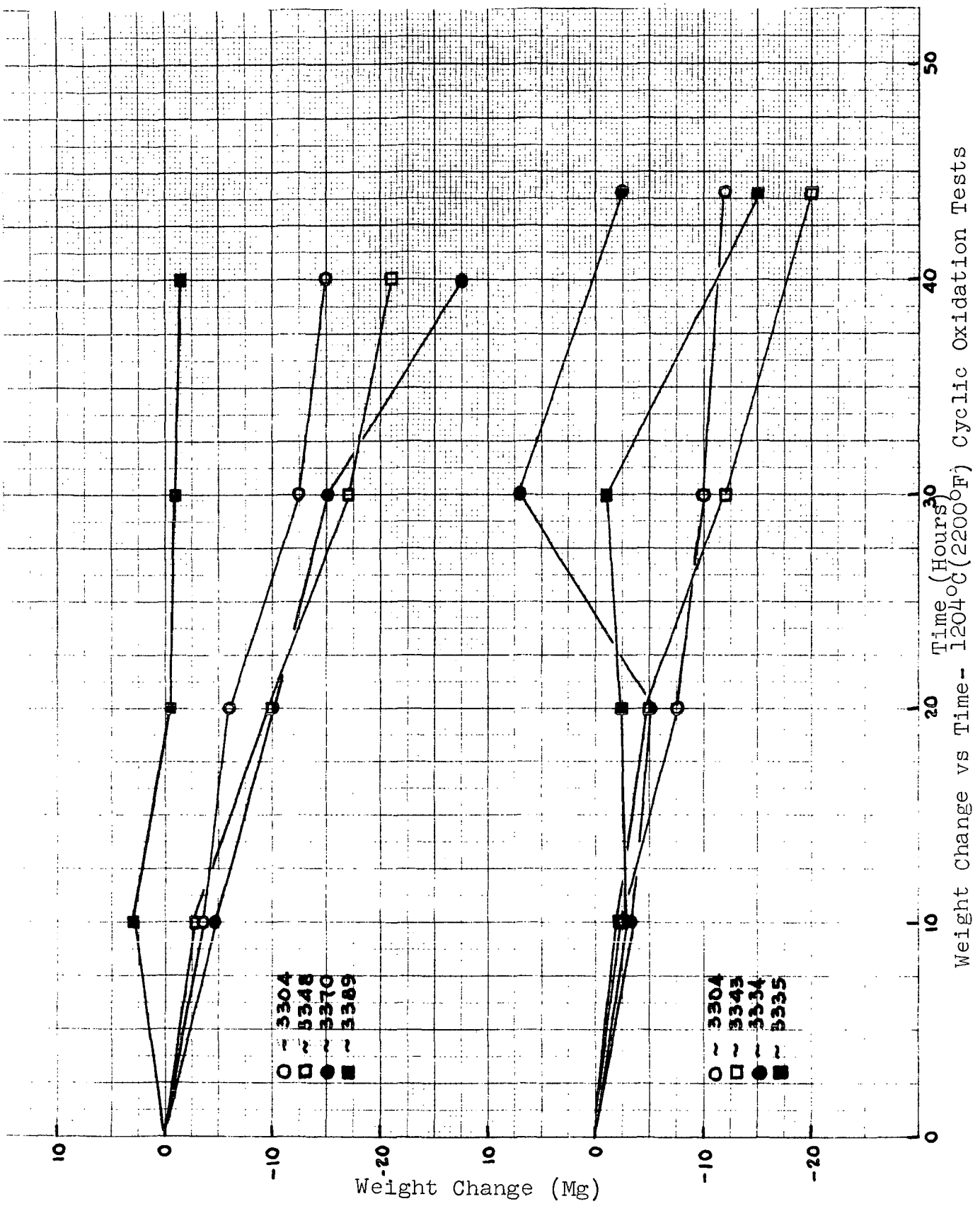


FIGURE F-3 - OXIDATION BEHAVIOR OF EXPERIMENTAL TDNiCr BASE ALLOYS

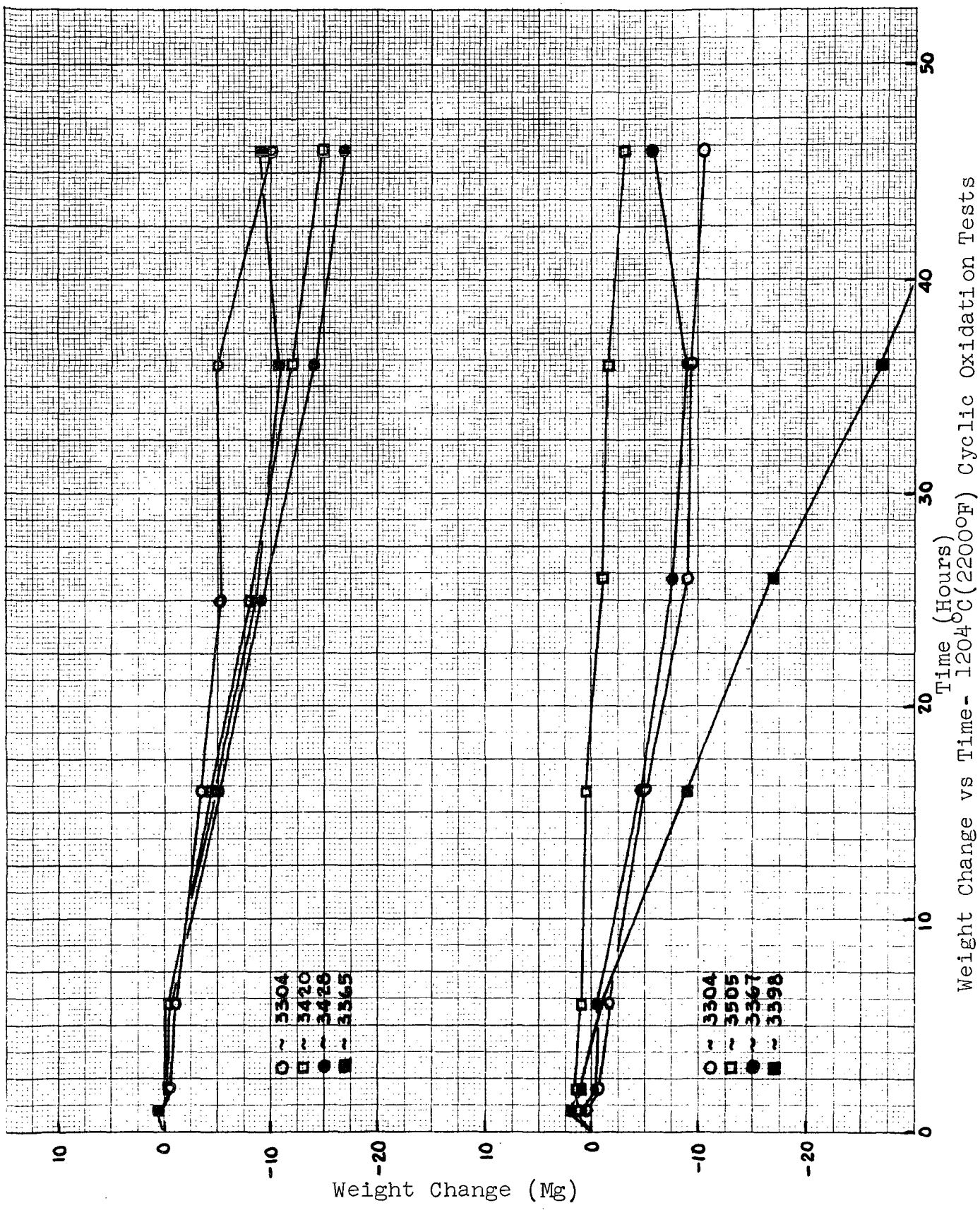


FIGURE F-4 - OXIDATION BEHAVIOR OF EXPERIMENTAL TDNiCr BASE ALLOYS

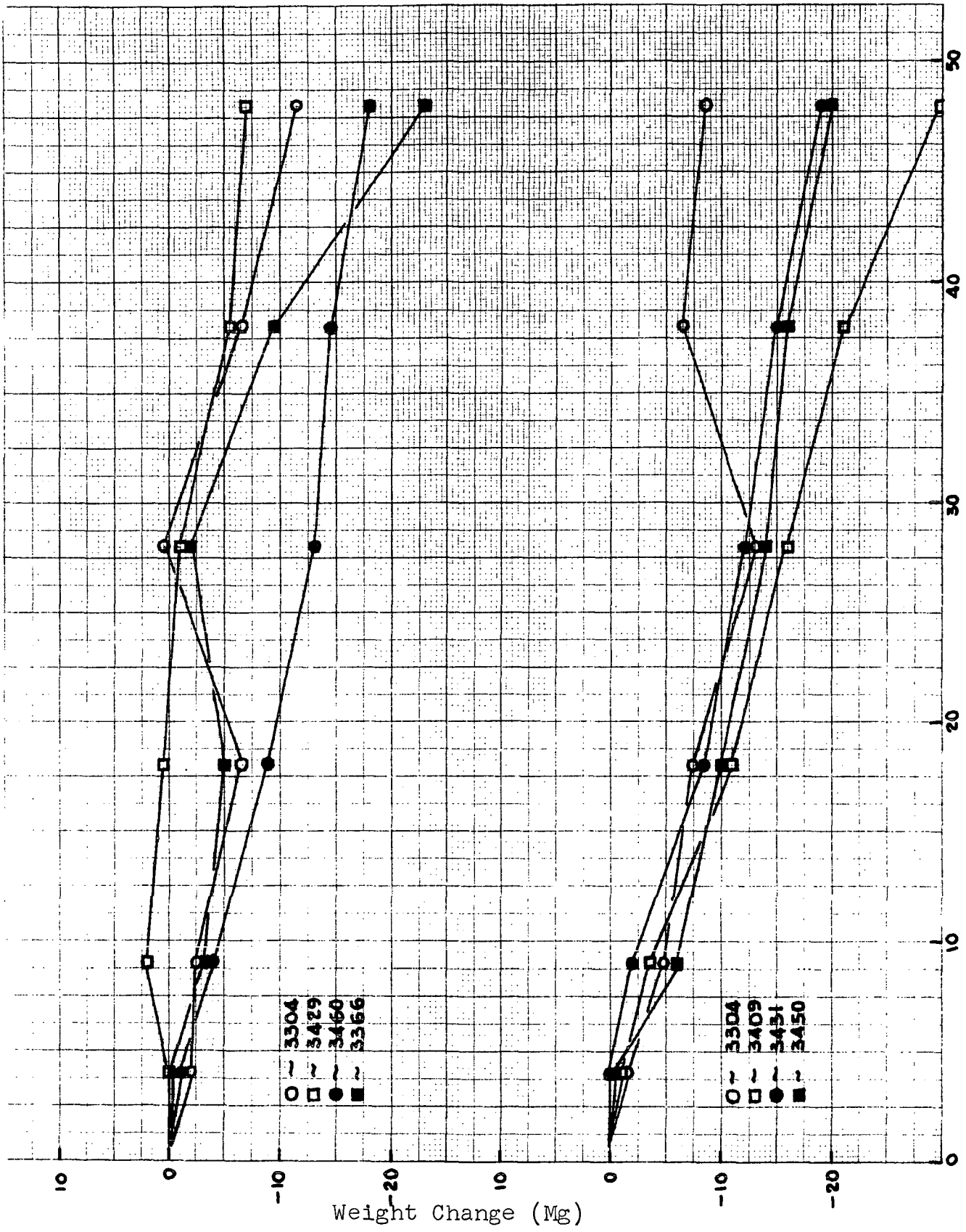


FIGURE F-5 - OXIDATION BEHAVIOR OF EXPERIMENTAL TDNiCr BASE ALLOYS

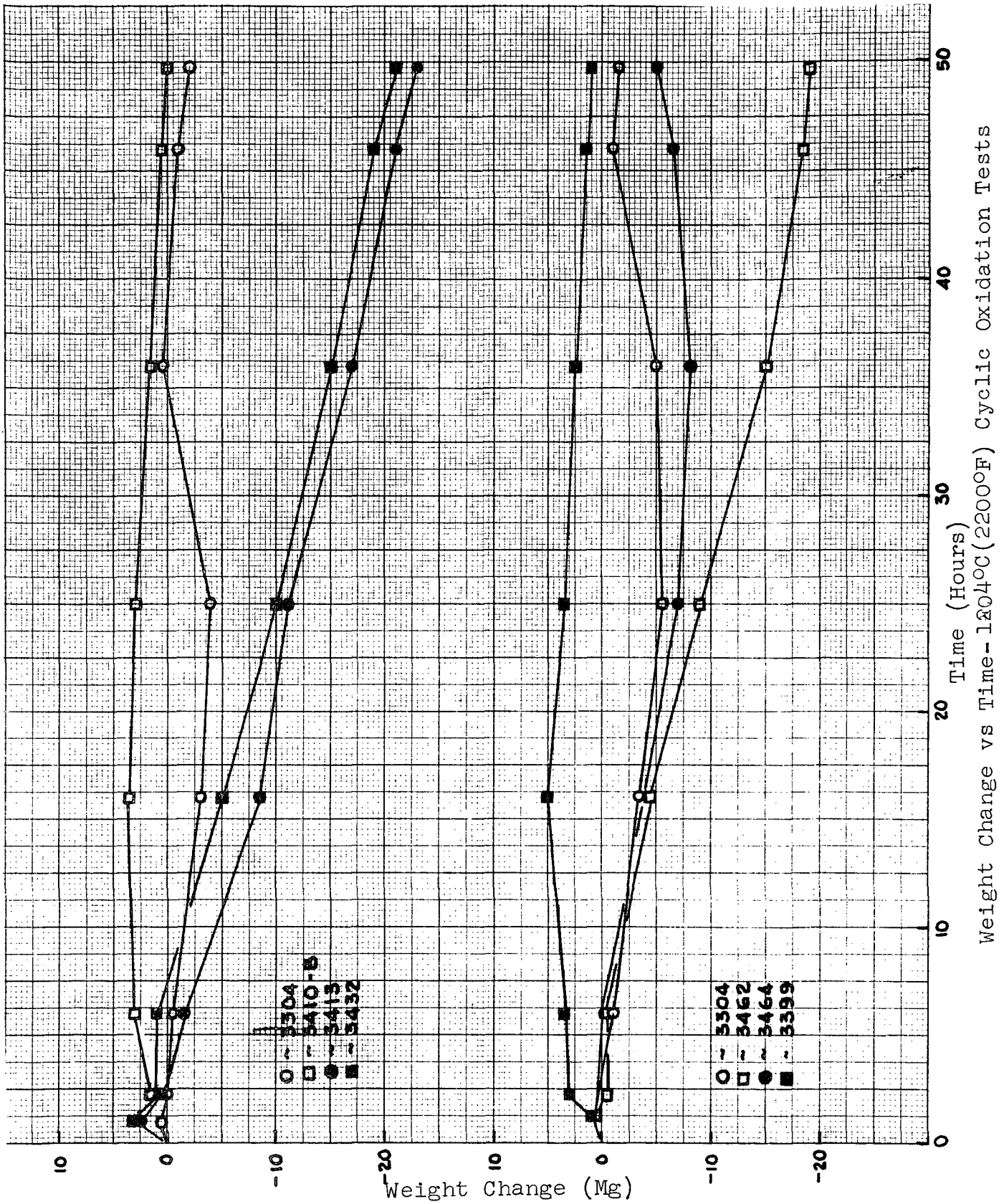


FIGURE F-6 - OXIDATION BEHAVIOR OF EXPERIMENTAL TDNiCr BASE ALLOYS

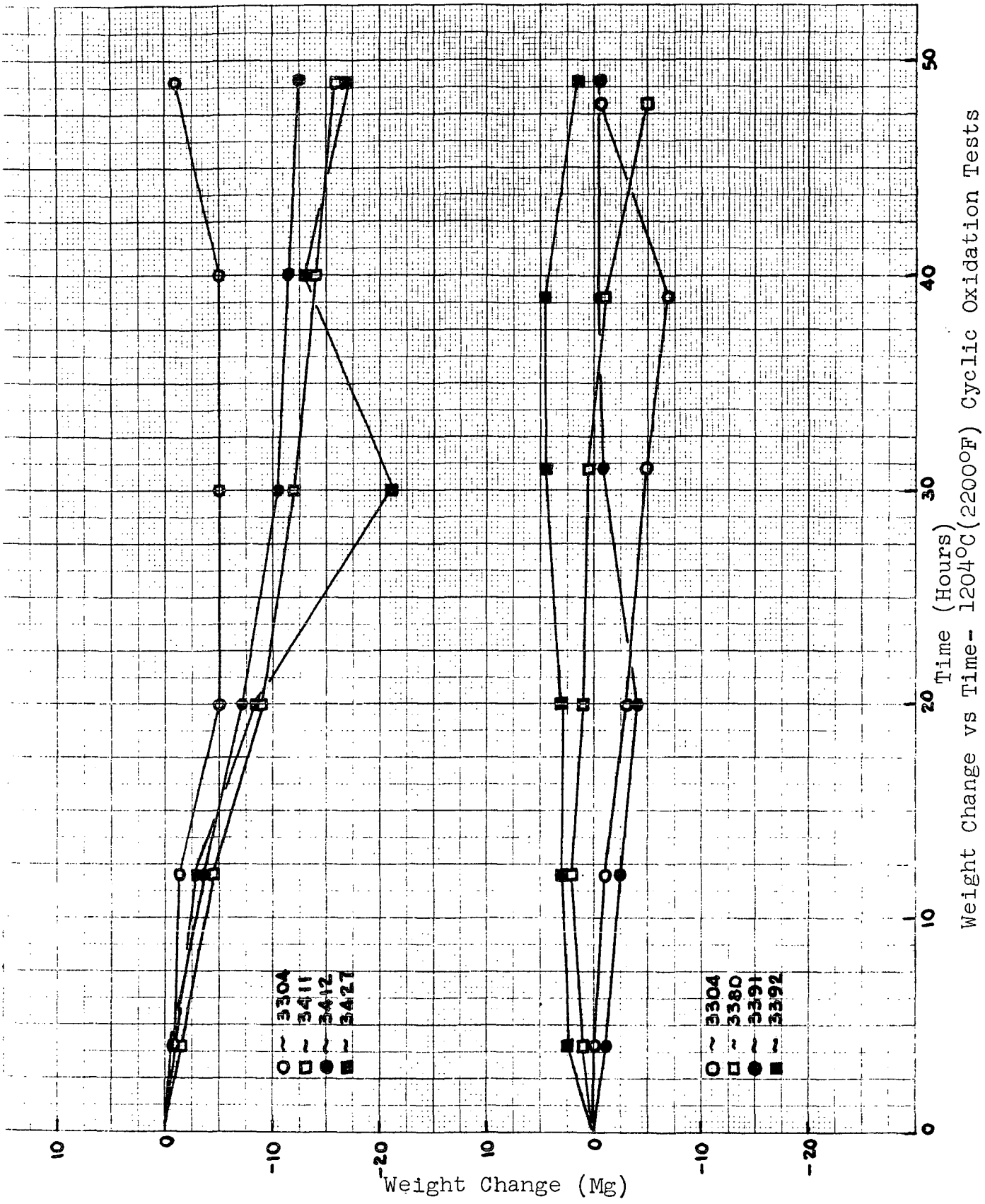


FIGURE F-7 - OXIDATION BEHAVIOR OF EXPERIMENTAL TDNiCr BASE ALLOYS

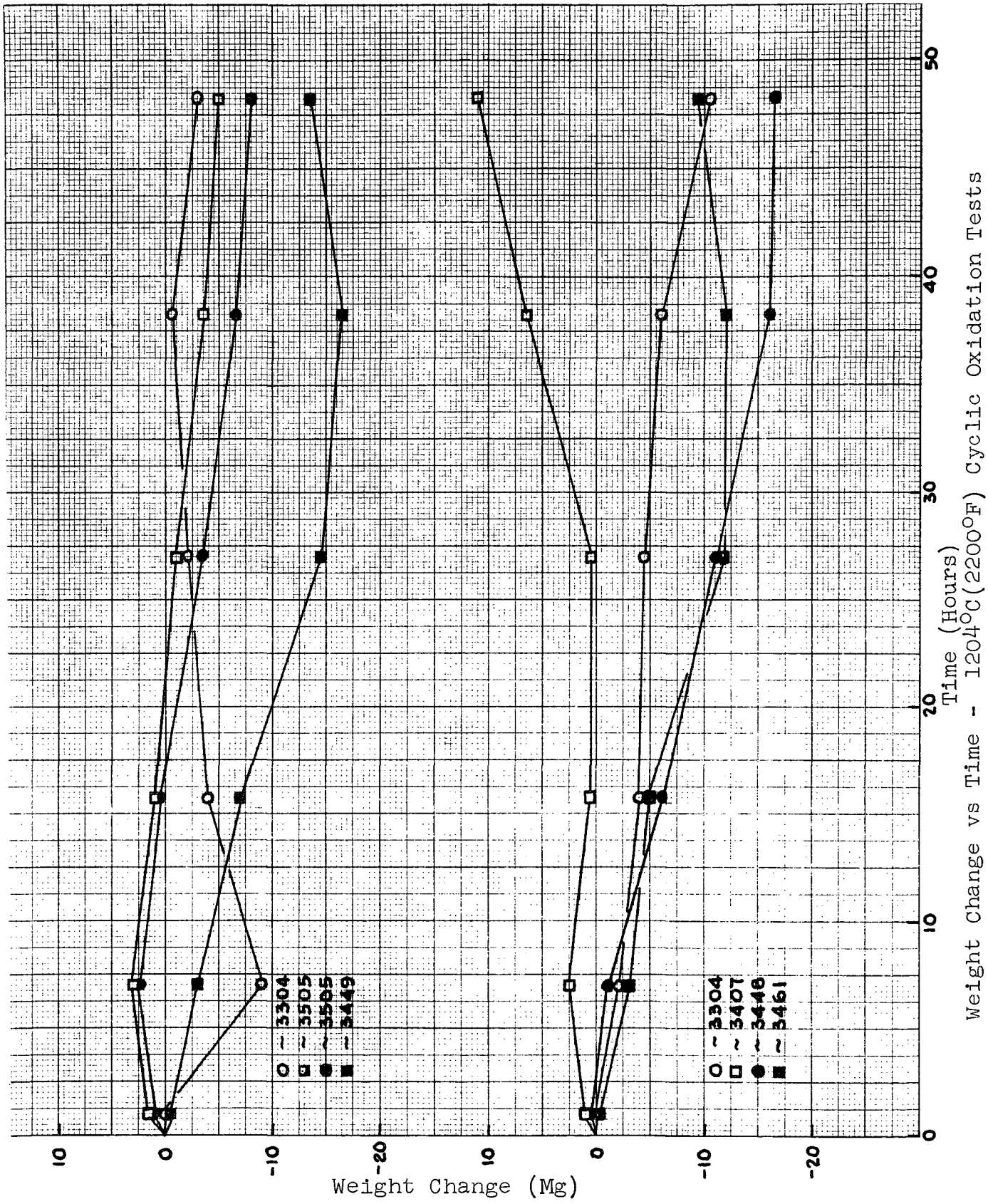


FIGURE F-8 - OXIDATION BEHAVIOR OF EXPERIMENTAL TDNiCr BASE ALLOYS

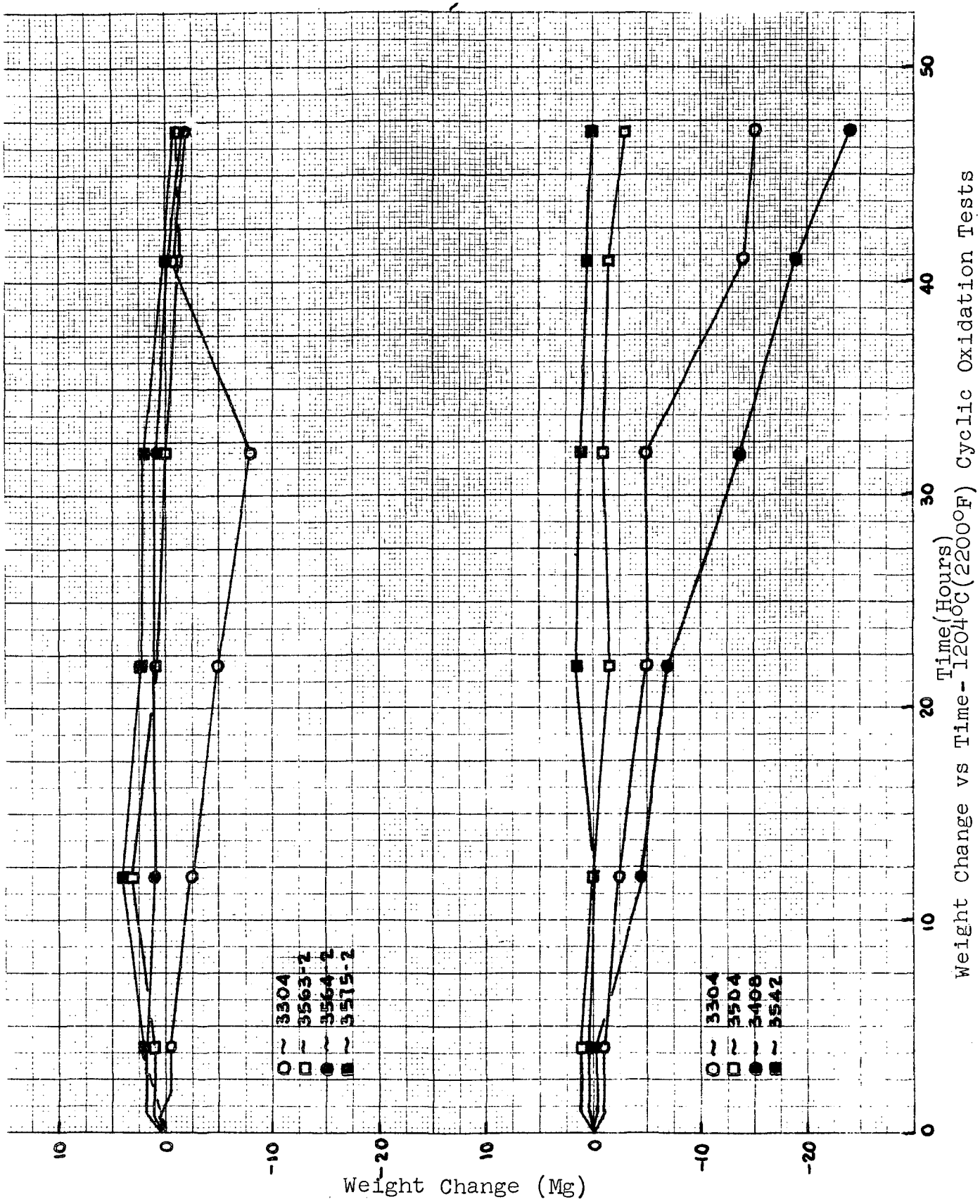


FIGURE F-9 - OXIDATION BEHAVIOR OF EXPERIMENTAL TDNiCr BASE ALLOYS